

# Hunting for TeV Scale Strings at the LHC<sup>1</sup>

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## Abstract

In this paper I review the possibility of TeV scale strings that may be detectable by the Large Hadron Collider (LHC). This possibility was investigated extensively in a series of phenomenological papers during 1984-1985 in connection with the Superconducting Super Collider (SSC). The work was mainly based on a model independent systematic parametrization of scattering amplitudes and cross sections, for Standard Model particles, quarks and leptons, that were assumed to behave like strings, while gluons, photons,  $W^\pm$ ,  $Z$  were taken as elementary. By using Veneziano type beta functions consistent with crossing symmetry, duality and Regge behavior, bosonic or fermionic resonances in each channel were included, while the low energy behavior was matched to effective field theory non-renormalizable interactions consistent with the Standard Model  $SU(3) \times SU(2) \times U(1)$  gauge symmetry as well as global flavor and family symmetries. The motivation for this approach at that time was the possible compositeness of quarks and leptons but the same phenomenological approach would apply effectively with the modern additional motivations for TeV scale strings, such as the hypothesis of D-branes with large extra dimensions. Because some of the main theoretical and phenomenological work of that time appeared only in the 1984 Snowmass and other proceedings, the results of the investigations have been inaccessible to most researchers and consequently have been largely forgotten. Meanwhile similar approaches are being explored by other researchers. Given the renewed interest in the old results, the purpose of the current paper is to make them readily available.

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## I. STRINGS AT THE LHC?

It is everyone's hope that the LHC is on the verge of discovering new physics at the TeV scale. On the basis of the spectacular success of the Standard Model, the one sure thing that is expected at the LHC energies is the Higgs particle or something else that imitates it. Of course clarifying the nature of the electroweak phase transition will be one of the main tasks at the LHC. The Standard Model is consistent with several speculative scenarios of new physics at the TeV scale, including supersymmetry, technicolor, compositeness, large extra dimensions. While some of these, such as supersymmetry, are better understood with reliable computational tools, others such as technicolor and compositeness necessarily remain more obscure due to the presence of an assumed less understood strong interaction. There are no strong physical indications that make it necessary for any of these new physical possibilities to emerge at the TeV scale. Nevertheless none can be eliminated either at this stage.

In this paper I will concentrate on how to hunt for signals of string-like physics at the TeV scale. The strings I have in mind could be either elementary, as in the case of large extra dimensions, or flux tubes of a QCD-like new strong interaction. Spectacular signals would be detected if the string scale happens to be reachable at the LHC energies. The formalism and the analysis presented here does not attempt to distinguish between the underlying physics because it was conceived in 1984 at a time before the first string revolution, and therefore it concentrates on compositeness. However, the same approach is easily adapted to the more modern ideas of strings and branes with large extra dimensions. If string-like signals are detected, further analysis can in principle be performed to distinguish between specific phenomena that may be more characteristic of one scenario versus the other (such as black holes).

For a couple of years before and after the 1984 SSC workshop at Snowmass, I pursued the phenomenological exploration of string-like physics at the TeV scale. At that time this study was motivated by the idea that there may be a new strong interaction at the TeV scale that may hold together preons inside quarks and leptons. To observe the effects of such a strong interaction I suggested to look for string-like behavior at the TeV scale, similar to strings (or flux tubes) that occur in QCD. With this in mind I was the first to formulate the phenomenological parametrization of cross sections and amplitudes with Veneziano-type beta functions, to describe all relevant processes that involved "composite" quarks and leptons [1][2]. Then together with collaborators that included Albright, Barbieri, Dine, Gunion, Hinchliffe, Eilam and many other phenomenologists and some experimentalists, this type of phenomenology was pursued for many potential experiments at the SSC. This work was presented in [1]-[13] most of which was published in proceedings of conferences that are not easily accessible. Therefore the papers that appeared in proceedings are being made available as attachments to the current preprint.

Now there are more motivations, in addition to compositeness, to pursue string-like physics at the LHC. The idea of D-branes and large extra dimensions discussed by Arkani-Hamed, Di-

mopoulos, Dvali, Antoniadis, Randall and Sundrum [14]-[17] has revived the interest for possible strings at the LHC energies. Although the underlying physics is quite different than compositeness, the method of phenomenological investigation, and many of the signals are very similar. If string-like behavior is miraculously found at the LHC, when enough data becomes available one can develop tests to distinguish the different physical phenomena as described in the details of the amplitudes, but the overall phenomenological approach is common and model independent. Motivated by this view, Cullen, Perelstein and Peskin [18] suggested a phenomenological analysis which was quite similar to that of [1][2] to investigate the possibility of strings. More recently Lüst, Stieberger and Taylor [19], discussed an approach which again is similar to the 1984 proposal in [1][2], although they proposed more detailed computations of amplitudes using string theory adapted to the LHC. Given the revived interest, and the approaching possibility of new discoveries at the LHC, the material attached to this preprint may be helpful in the upcoming investigations.

The following are the abstracts of the papers listed in [1]-[13]. The interested reader is invited to consult the original literature. In reading these papers, instead of the SSC now one should substitute the LHC., and for the most part one can easily substitute the idea of compositeness by a more general idea that relates to strings at the TeV scale. Differences in the underlying physics would appear in the details of the amplitudes.

- *Physics Above the preon scale, by I. Bars* [1]: The preon scale may be comparable or lower than the parton-parton center of mass energies that will be reached at the SSC. Then we expect resonance, Regge behavior, diffractive scattering and scaling phenomena to occur in analogy to the physics of low energy hadronic reactions. Such physical phenomena in the hadronic world could approximately be described by duality or string-like behavior (color flux tube confinement). To discuss this type of physics quantitatively for composite quarks and leptons we propose a model of scattering amplitudes and cross sections based on Veneziano type beta functions that correspond to duality diagrams for preons. All dimensionless parameters are fixed by analogies to low energy hadronic physics. Topics discussed include the preon scale, the Regge spectrum of composite states, model independent invariant amplitudes, preon models, preon diagrams and corresponding duality amplitudes, differential cross sections.
- *Probing for Preon Structure via Gluons, by C. Albright and I. Bars* [2]: Gluons form an important fraction of the partons at small  $x$  in  $\bar{p}p$  scattering at SSC energies. Therefore, gluon reactions at the SSC may be expected to yield important signals for compositeness, if the preon scale is a few TeV. Here we develop a quantitative method for estimating many gluon scattering processes. Some of our estimates are model independent. We also propose explicit formulas for various scattering amplitudes based on a Veneziano-type beta function model that exhibits resonances and Regge behavior. Many interesting spectacular signatures are suggested in the resonance region, where massive vector bosons and/or

excited and exotic quarks and leptons could be produced.

- *Can the Preon Scale be Low?* by I. Bars [3]: The preon scale  $\Lambda_p$  is bound from below by rare or unobserved processes [20] and from above by the cosmological abundance of stable heavy composites [21]. On the other hand composite models can be tested by the SSC or by low energy experiments only if  $\Lambda_p$  is allowed to be at most 5-10 TeV. In search of such models we re-examine some conditions that must be fulfilled if  $\Lambda_p$  is small, and point out the possibility of certain mechanisms that could avoid the dangerous rare processes. In addition, certain properties of exotic composite particles, their possible role in breaking the electroweak symmetry and in producing observable signals beyond the standard model are also discussed.
- *High  $p_T$  photon production and compositeness at the SSC*, by J.F. Owens, T. Ferbel, M. Dine and I. Bars [4]: The yield for direct photons for  $p_T \geq 1$  TeV is large enough to probe predictions of conventional QCD as well as to examine consequences of the compositeness of quarks at the scale of  $\sim 5$  TeV.
- *Low Energy Signals of Composite Models*, by R. Barbieri, I. Bars, M. Bowick, S. Dawson, K. Ellis, H. Haber, B. Holdom, J. Rosner, M. Suzuki [5]: Some signals of compositeness that represent deviations from the standard model at low energies are discussed. Emphasis is given to exotic composites, strong P,C violation beyond weak interactions and small deviations in relations among the parameters of the standard model. Such effects may be detected at energies obtainable at CERN, LEP and the SSC.
- *Searching for quark and lepton compositeness at the SSC*, by C. Albright, I. Bars, K. Braun, M. Dine, T. Ferbel, H.J. Lubatti, W.R. Molzon, J. F. Owens, S.J. Parke, T. R. Taylor, M. P. Schmidt, H. Snow [6]: We examine a variety of issues connected with searching for compositeness at the SSC. These include effects of resolution, alternative methods of looking for deviations from QCD predictions, advances of polarized beams, and effects of compositeness on photon detection. We also consider how physics may look if the compositeness scale is as low as a few TeV.
- *The effects of quark compositeness at the SSC*, by I. Bars and I. Hinchliffe [7]: The effects of composite quarks on jet cross sections at the Superconducting Super Collider (SSC) is discussed with particular emphasis upon the rates for jet energies above the composite scale. Our main conclusion is that compositeness physics dominates other exotic physics if the compositeness scale is in the SSC range. Different composite models are compared in order to examine whether discrimination between them is possible.
- *Leptonic signals for compositeness at hadron colliders*, by I. Bars J. F. Gunion and M. Kwan [8]: We consider composite models in which quarks and leptons have constituents in common. Detailed amplitudes for subprocesses of the type quark+antiquark

$\rightarrow$  lepton+antilepton are constructed using the presumed similarity between QCD and compositeness/pre-color interactions. We demonstrate that sensitivity to compositeness scales,  $\Lambda$ , as high as 100 TeV to 300 TeV may be achievable at a supercollider with center-of-mass energy,  $\sqrt{s} = 40$  TeV. For moderate values of  $\Lambda$  ( $\leq 15$ -20 TeV) cross sections are several orders of magnitude larger than the background Drell-Yan estimate, reflecting the presence of the new underlying strong interaction. Furthermore, some models exhibit a resonant structure in lepton anti-lepton pair mass spectra, near  $M_{l\bar{l}} \approx \Lambda$ , corresponding to heavy preon-antipreon composite states. If  $\Lambda$  is in the SSC range, compositeness would probably dominate the cross sections of most processes and could readily be explored experimentally. Finally, at  $S\bar{p}pS$  energies,  $\sqrt{s} \approx 540$  TeV, observation of lepton-antilepton pair mass spectra with no deviation from the standard-model Drell-Yan prediction at  $M_{l\bar{l}} \approx 150$  TeV would place limits on  $\Lambda$  in the range 1.5 to 3 TeV.

- *Signals for compositeness in  $e^+e^-$  to  $e^+e^-$  and  $\mu^+\mu^-$ , by I. Bars J. F. Gunion and M. Kwan [9]:* Theories in which leptons are composite lead to additional contributions (beyond those from the standard model) to the amplitudes for  $e^-e^+ \rightarrow e^-e^+$  and  $e^-e^+ \rightarrow \mu^-\mu^+$ . Detailed models, constructed by analogy between QCD and compositeness/precolor interactions lead to specific forms for these extra terms. We demonstrate that compositeness scales  $M$  as high as 4–7 TeV may be probed using  $e^-e^+$  collision machines currently available and planned for the near future. Sensitivity to the type of composite model and its parity-violation structure is demonstrated. In particular we point out that there are no standard-model contributions to the scattering  $e^-e^+ \rightarrow \mu^-\mu^+$  when the incoming  $e^-$  and  $e^+$  both have the same helicity. Observation of a nonzero cross section in such a helicity scattering state is prima facie evidence of flavor-changing vector currents in the  $t$  channel or scalar currents connecting the  $e$  and  $\mu$  lepton sectors in the  $s$  channel.
- *New physics signatures in polarized  $e^-e^+$  experiments, by I. Bars, Gad Eilam, J. Gunion [10]:* In  $e^-e^+$  experiments with the  $e^-$  beam transversally polarized we compute an asymmetry and show that in the near future it can serve as a probe of “new physics” up to scales of order 20 TeV. The asymmetry is proportional to the mass of the final state fermion and hence is largest in the production of the top quark (unless there exists a heavier fermion). There is practically no standard model background to this asymmetry. For example, at center of mass energies of 42 GeV, compositeness scales of 5, 10, 15, 20 TeV yield asymmetries of 14.4%, 3.8%, 1.7%, 0.9% respectively. We have also found substantial deviations in the unpolarized cross sections. For example at 200 GeV and  $\cos\theta = 0.7$  this deviation is estimated as 355%, 50%, 19%, 10% at the above compositeness scales. Our general analysis is applicable to other “new physics” as well.
- *Composite quarks and leptons, tests and models, by I. Bars [13]:* The theory and tests of composite quarks and leptons are reviewed. A model that addresses the puzzle of lepton-quark symmetry within a family is presented. A dynamical mass generating mechanism is

discussed. The present evidence that requires the compositeness scale to exceed 3 TeV is reviewed and further tests at the SLC, LEPI and LEP II that would be sensitive to scales as large as 20-25 TeV are emphasized. Signals that would correspond to compositeness at SSC energies are described.

I hope this compilation of old results would be helpful in the analysis of data as well as in the construction of new models. One needs to keep an open mind on the possible underlying physics until the LHC data becomes available. If and when some candidate events that fit the string-like description are seen, it would then be very interesting to fit to the general amplitudes in [1][2] to figure out the details of the underlying physics.

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# PHYSICS ABOVE THE PREON SCALE<sup>†</sup>

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## SUMMARY

The preon scale may be comparable or lower than the parton-parton center of mass energies that will be reached at the SSC. Then we expect resonance, Regge behavior, diffractive scattering and scaling phenomena to occur in analogy to the physics of low energy hadronic reactions. Such physical phenomena in the hadronic world could approximately be described by duality or string-like behavior (color flux tube confinement). To discuss this type of physics quantitatively for composite quarks and leptons we propose a model of scattering amplitudes and cross sections based on Veneziano type beta functions that correspond to duality diagrams for preons. All dimensionless parameters are fixed by analogies to low energy hadronic physics. Topics discussed include the preon scale, the Regge spectrum of composite states, model independent invariant amplitudes, preon models, preon diagrams and corresponding duality amplitudes, differential cross sections.

## I. THE PREON SCALE

At energies far below the preon scale,  $E \ll \Lambda_p$ , composite quarks and leptons are described by an effective Lagrangian

$$L_{\text{eff}} = L_{\text{standard}} + L_{\text{non-renormalizable}} \quad (1.1)$$

where the non-renormalizable terms have powers of  $1/\Lambda_p$  for correct dimensionality. We assume that gluons, photon and  $W, Z$  are elementary. Then they couple gauge invariantly in the effective theory. The underlying preon theory must have a sufficiently large number of preon-flavor chiral symmetries in order to suppress rare or unobserved processes that may be mediated by  $L_{\text{non-renormalizable}}$  -- otherwise  $\Lambda_p$  must be very large to suppress them. The strongest bounds on  $\Lambda_p$  come from 4-fermi interactions as first discussed in ref. 1, 2 and later in the Snowmass 82 study.

Preon models with such symmetries have been constructed<sup>1,2</sup>. These models, which satisfy a large number of theoretical requirements, show that the repetitive family patterns can be understood as a consequence of compositeness. A general, model independent, theorem<sup>3,4</sup> states that, for repetitive quark plus lepton families, one cannot find preon symmetries that suppress all the effective family changing 4-fermi terms of the form

$$\frac{\lambda^2}{2\Lambda_p^2} s_{\gamma\mu} \frac{(1+\gamma_5)}{2} d_{\gamma\mu} \bar{e}_{\gamma\mu} \frac{(1+\gamma_5)}{2} \mu_{\gamma\mu} + (\text{preon symmetric terms}) \quad (1.2)$$

where o-subscripts indicate that these are the states before mass mixing. The constant  $\lambda$  is estimated to be of order 1 by analogy to  $\rho$ -exchange in hadronic reactions ( $m \approx 5\Lambda_{\text{QCD}}$  and  $\Lambda_p$  analogous to  $\Lambda_{\text{QCD}}$ ). Assuming that<sup>5</sup> the mixing angles are not large, the unobserved decays  $K \rightarrow \mu e$  and  $K \rightarrow \pi \mu e$ , require the bound<sup>2</sup>  $\Lambda_p > (20-30)\text{TeV}$ . This bound corresponds to the most intuitive situation. If true, the chances of seeing substantial signals of compositeness at the SSC are small.

Possible mechanisms that avoid this bound are less intuitive. For example<sup>6</sup>, if mixing angles are large in the lepton sector [remember that ups and

downs mix separately even if the relative up-down angles are small] such that  $e_{\gamma\mu} \approx \tau$  (or some other lepton heavier than the  $\tau$ ), while  $s_{\gamma\mu}, d_{\gamma\mu}, \mu_{\gamma\mu}$  are close to the mass eigenstates  $s, d, \mu$ , then  $K_L$  and  $K_S$  cannot decay with a family changing interaction. A model of this type, with no other problematic 4-fermi interaction including mixing angles, is given in another article in these proceedings. Another way which completely eliminates such dangerous terms is to divorce the quark family quantum numbers from those of the leptons. For example, we may have family preons which also carry color to construct quarks, plus a totally different set of colorless family preons to construct leptons. Then the family group for quarks is different than the family group of leptons. The cost we pay in such a model is to give up any simultaneous understanding of the origin of quark plus lepton families. Other, less attractive, avenues along similar lines are clearly possible.

In this paper we assume that  $\Lambda_p$  is not restricted by rare  $K_L$  or  $K_S$  decays. Then the remaining model independent bounds presently known to be unavoidable by symmetries are much less severe. They come from Bhabha scattering and the anomalous magnetic moment of the muon, and are easily satisfied if  $\Lambda_p$  is of order TeV. If this is the case we should see plenty of dramatic compositeness signals at the SSC. Furthermore, at SSC energies the effective theory of eq. (1.1) is not adequate and we must make a model of amplitudes by analogies to low energy (1-20GeV) hadronic physics as proposed here.

In this paper we will use the mass of the preon-antipreon composite vector meson,  $M_V$ , as the characteristic scale of compositeness. This corresponds to  $\Lambda^*$  of refs. (6,7),  $M_V \approx \Lambda^*$ . Thus, the lower bound on  $M_V$  is  $M_V > 1\text{TeV}$ . Note however that in QCD the analogous state satisfies  $m \approx (3-5)\Lambda_{\text{QCD}}$  and therefore we might expect  $M_V \approx (3-5)\Lambda_p$  (note  $\Lambda^*_{\text{QCD}}$  is not  $\Lambda_p$ ). We expect that the radius of composite quarks and leptons is  $R \approx 1/\Lambda_p$  (as in QCD) and on the basis of the geometrical model we anticipate that the total cross section is of the order of

$$\sigma^{\text{tot}} \approx 2\pi R^2 \approx (9 \text{ to } 25) \frac{2\pi}{M_V^2} \quad (1.3)$$

This normalization will be reflected in the asymptotic behaviour of the Pomeron contributions to the amplitudes given in the rest of the paper.

There may also be a (model dependent?) cosmological upper bound<sup>3</sup>  $M_V < 250\text{TeV}$ . The existence of such a bound is encouraging from the point of view of the SSC. The bound may be lowered if galaxy clustering is taken into account, a point which was not discussed in ref. 3.

## II. SPECTRUM OF COMPOSITE STATES

The dynamics that confine the preons are similar to QCD dynamics that confine the quarks. Therefore, we may draw parallels between hadrons and composite quarks and leptons. For example, we suggest that composite fermions and bosons lie on approximately linear Regge trajectories reflecting approximate string (precolor flux tube) dynamics. The major difference from QCD is that a preon theory is expected to have almost exact chiral symmetries leading to

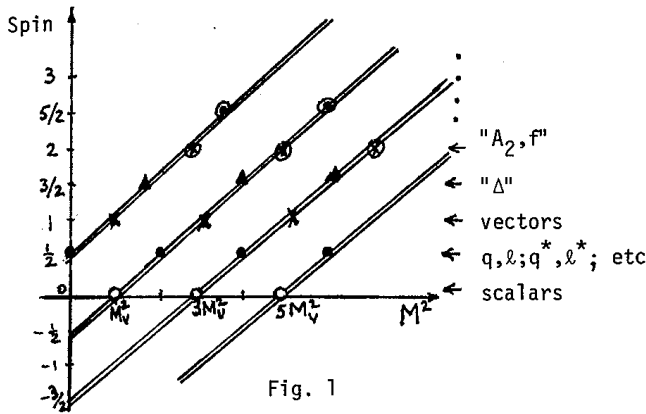


massless fermions (quarks & leptons) instead of massless pions. Therefore, the fermion trajectory  $\alpha(s)$  (preon-preon-preon) must have intercept  $1/2$ , instead of  $-1/2$  in QCD. The vector meson trajectory  $\alpha(s)$  (preon-antipreon) can be taken with intercept  $1/2$ , just as the rho in QCD. The scalar-pseudoscalar trajectory  $\alpha(s)$  (preon-antipreons) can be taken at the level of the daughter of V, with intercept  $-1/2$ , instead of 0 for the pion trajectory in QCD. Thus, we propose

$$\alpha^F(s) \approx \alpha^V(s) \approx 1 + \alpha^L(s) \approx \frac{1}{2} + \alpha's \quad (2.1)$$

The slope  $\alpha' = M_V^2/2$  is chosen so that at the mass of the vector meson  $\alpha(M_V^2) = 1$ , as required.

With these trajectories we introduce a Chew-Frauchi plot of the expected heavy states with masses of order  $M_V$ , as in Fig. 1.



Thus the mass of the excited states for various spins and mass levels can be guessed as:  $M_V$  for vectors, scalars;  $\sqrt{2}M_V$  for excited spin  $1/2$  or  $3/2$  quarks/leptons;  $\sqrt{3}M_V$  for spin 2 bosons, excited vectors, excited scalars, etc.

Since the preon symmetries are only slightly broken on the scale of  $M_V$ ,  $\Delta m \ll M_V$ , we expect a high degree of near degeneracy (up to  $\Delta m$ ) among the heavy states with various color, lepton, flavor or family quantum numbers. For example, an octet vector meson (color-anticolor) is nearly degenerate with a lepto-quark vector meson, or with a family changing vector meson. Similarly for scalars, spin  $1/2$ , spin  $3/2$  etc. states. Only the nearly massless spin- $1/2$  quarks and leptons show substantial mass splittings since  $\Delta m$  is large compared to 0.

There may be different trajectories for composites (e.g. vectors) made of left handed preons versus right handed preons since precolor forces do not conserve parity. In this paper, as a first approximation this will be ignored. However, this point has to be revised for a study of parity violation in preon models.

Additional exotic fermionic states with high color or high weak-isospin may be present depending on the theory. These have zero mass in the limit of exact preon chiral symmetries. Thus  $\Delta m$  for such states, which is independent than  $M_V$ , must be arranged to be sufficiently large for such fermions not to have shown up at present energies. The trajectory for such states would then have an intercept substantially lower than  $1/2$ .

Heavy bosonic states ( $\bar{V}$ ,  $\bar{\Sigma}$ , etc.) of the type dipreon-diantipreon may be present. These are

particularly expected in theories with direct product precolor groups. Their mass is at least as large as  $M_V$ . Their trajectories actually may lie somewhat lower than those of V,  $\Sigma$  etc.

### III. MODEL INDEPENDENT INVARIANT AMPLITUDES

Here we present a general, model independent, formalism for massless fermion-antifermion  $f_1 \bar{f}_2 \rightarrow f_3 \bar{f}_4$  and fermion-fermion  $f_1 f_2 \rightarrow f_3 f_4$  scattering that is applicable to  $f_i$  = any quark or lepton (or exotic spin  $1/2$  fermions). We have found that the most general amplitude, compatible with preonic left-handed and right handed flavor chiral symmetries can be written as follows

$$\begin{aligned} M_{f_1 \bar{f}_2 \rightarrow f_3 \bar{f}_4} = & A^{LL} \bar{u}_{3L} \gamma^\mu u_{1L} \bar{v}_{2L} \gamma_\mu v_{4L} + A^{RR} \bar{u}_{3R} \gamma^\mu u_{1R} \bar{v}_{2R} \gamma_\mu v_{4R} \\ & + B^{LR} \bar{u}_{3L} \gamma^\mu u_{1L} \bar{v}_{2R} \gamma_\mu v_{4R} + B^{RL} \bar{u}_{3R} \gamma^\mu u_{1R} \bar{v}_{2L} \gamma_\mu v_{4L} \\ & - C^{LR} \bar{u}_{3L} \gamma^\mu v_{4L} \bar{v}_{2R} \gamma_\mu u_{1R} - C^{RL} \bar{u}_{3R} \gamma^\mu v_{4R} \bar{v}_{2L} \gamma_\mu u_{1L} \end{aligned} \quad (3.1)$$

and

$$\begin{aligned} \frac{d\sigma}{dt}(f_1 \bar{f}_2 \rightarrow f_3 \bar{f}_4) = & \frac{1}{16\pi s^2} \{ u^2 [ |A^{LL}|^2 + |A^{RR}|^2 ] + s^2 [ |B^{LR}|^2 + |B^{RL}|^2 ] \\ & + t^2 [ |C^{LR}|^2 + |C^{RL}|^2 ] \}. \end{aligned} \quad (3.2)$$

Four more amplitudes  $D^{LR}$ ,  $E^{LR}$ ,  $D^{RL}$ ,  $E^{RL}$  which would have appeared as the coefficients of  $\bar{u}_{3L} u_{1R} \bar{v}_{2L} v_{4R}$ ,  $\bar{u}_{3L} v_{4R} \bar{v}_{2L} u_{1R}$  and their parity conjugates have been set equal to zero, since preonic left and right chiral symmetries demand it. Any 4-fermion interaction can always be Fierz transformed to our form. Our formalism in terms of left and right projections is necessary for the present analysis, but it can be related to old work on nucleon-nucleon scattering.

The general form of the amplitude and cross section for  $f_1 \bar{f}_2 \rightarrow f_3 \bar{f}_4$  can be obtained from the above by crossing symmetry, which amounts to replacing  $v_2 \rightarrow u_2$ ,  $v_4 \rightarrow u_4$  in (3.1) and interchanging the explicit  $s \leftrightarrow u$  in the curly brackets in (3.2). If the two processes involve just the correct fermions so that they are crossing symmetric reactions (e.g.  $uu \rightarrow d\bar{d}$  and  $ud \rightarrow du$ ) then the amplitudes are also related by interchanging  $s \leftrightarrow u$  in the functional dependence of each invariant amplitude  $A(s, t, u) \leftrightarrow A(u, t, s)$ , etc. Since we can always find an  $f_1 \bar{f}_2 \rightarrow f_3 \bar{f}_4$  reaction which is crossing symmetric to a given  $f_1 f_2 \rightarrow f_3 f_4$  reaction, it is sufficient to work out in detail just the fermion-antifermion case.

When two or four of the fermions are quarks the amplitudes  $A^{LL}$  etc. are matrices carrying color indices and  $|A^{LL}|^2$  means summing over the final colors and averaging over the initial ones. For example when all four fermions are quarks, with color triplet indices given as  $f_1 \bar{f}_2 \rightarrow f_3 \bar{f}_4$ , we write

$$(A^{LL})_{bc}^{ad} = A_H^{LL} \delta_c^a \delta_b^d + A_V^{LL} \delta_b^a \delta_c^d \quad (3.3)$$

where  $A_H$ ,  $A_V$  are the amplitudes corresponding to color lines flowing horizontally (along the S-channel) or vertically (along the t-channel) (see the diagrams in Figs. 2-4). Then  $|A^{LL}|^2$  means

$$|A^{LL}|^2 = \frac{1}{9} \sum_{a,b,c,d} |(A^{LL})_{bc}^{ad}|^2 = |A_H^{LL}|^2 + |A_V^{LL}|^2 + \frac{2}{3} \text{Re}(A_H^{LL*} A_V^{LL}) \quad (3.4)$$

Similarly for the other amplitudes  $A^{RR}$ ,  $B^{LL}$ ,  $B^{RR}$ , etc.

In a parity conserving theory we would have half as many amplitudes since  $A^{LL} = A^{RR}$ , etc. However, preonic strong interactions (precolor gauge theory) generally do not conserve parity because of the need to preserve unbroken chiral symmetries<sup>1,2</sup>. Even so, in the remainder of this paper we will assume parity symmetry for these amplitudes for the sake of obtaining simple expressions that allow some first estimates of the cross section. This "approximation" should be revised for the very important study of parity violation in composite models. This implies that the spectrum may be left-right asymmetric so that intercepts of trajectories and the overall scale of the amplitudes should be adjusted accordingly as suggested in the previous section. Since this is mostly a model dependent issue it is completely ignored in the present attempt of obtaining a first quantitative estimate of the cross sections.

#### IV. MODELS

The role of QCD and electroweak forces in a theory of composite quarks and leptons is analogous to the role of electroweak forces for hadrons. Thus, scattering amplitudes receive contributions from QCD and electroweak forces as well as from the underlying precolor strong forces. At very low energies  $E \ll \Lambda$ , QCD + electroweak interactions dominate as described by eq. (1.1), just as electromagnetism dominates the interactions among hadrons at distances much larger than several fermi. However when the energies are large enough to probe the structure of the quarks and leptons  $E > \Lambda$ , the precolor forces, analogous to strong hadronic interactions, should take over. At that point different preon models can make different predictions. To see this quantitatively we have estimated the amplitudes for 4 different classes of models in the next section. These models differ from each other only in the general sense of the type of preons that carry color, lepton, flavor, family and chirality quantum numbers. Such preons label the diagrams that contribute to the amplitudes as indicated in Figs. 2-4.

##### Class A

Composite fermions are made of three spin- $1/2$  preons  $(PF^i\psi)$ , where  $\psi$  has the quantum numbers of the 16 members of one family,  $F^i$  with  $i=1,2,3,\dots$  carry the family quantum numbers but carries precolor so as to make a precolor singlet. In specific models the 16 component  $\psi$  may be purely left-handed, 8-left and 8-right handed, or a mixture of lefts and rights, as in  $10_{-5} + 5_{+1}$  of  $SU(5)$ . For specific examples see refs. <sup>1-4</sup>. The important distinguishing factor is that in Figs. 2-4,  $U_{L,R}$  and  $D_{L,R}$  carry both flavor and color, while family quantum numbers go along with  $F$ .

##### Class B

Composites have again the structure of  $(PF\psi)$ . However,  $F^i$ ,  $i=1,2,3$  correspond to color and  $i=4$  to lepton (or 4th color as in Pati-Salam).  $\psi$  has both flavor and family quantum numbers, e.g.  $U_L^a$   $a=1,2,3$  correspond to  $U_L^c, t_L$  etc. For a specific example see ref. 4. Thus, in figs. 2-4  $U_{L,R}$  and  $D_{L,R}$  do not carry color,  $F$  does!

##### Class C

Composite fermions are constructed from a spin-0

preon  $\phi$  and a spin- $1/2$  preon  $\psi$ :  $(\phi\psi)$ .  $\phi$  has only family quantum numbers, while a 16 component  $\psi$ =left L and/or right R, is assigned color-flavor quantum numbers as in class A.

##### Class D

The structure is similar to class C, but now  $\phi$  has both family and color, as in  $\phi^{ia}$   $i$ =family,  $a$ =color or lepton, while  $\psi$  has only flavor (up, down) and chirality left (L) or right (R).

The scalars  $\phi$  of models C,D may be thought of as a pair of fermionic preons, such as  $(PF)$  or  $(P\psi)$  of models A,B. In models with direct product precolor groups this may be particularly appropriate.

These four classes cover a large number of specific preon models. Other structures not covered above may also be possible. However, for the present purpose these four will be sufficient to illustrate some quantitative differences among preon models in  $pp$  or  $pp$  scattering as shown in table 1 and the cross sections of section 7.

#### V. AMPLITUDES AND DIAGRAMS

In this section we will explicitly give the QCD (lowest order) plus compositeness amplitudes for quark + antiquark + quark + antiquark. The case of quark + quark + quark is obtained by crossing as explained in sec. III. The important reaction quark + antiquark + lepton + antilepton (which modifies Drell-Yan) can be obtained by similar methods using similar diagrams and amplitudes as the ones given here and, of course, substituting electroweak interactions instead of QCD. Lepton pair production is omitted here for lack of space.

The reader who wishes to understand the details should carefully study the QCD and model A,B,C,D amplitudes of table 1 and the corresponding preon diagrams of Figs. 2-4. The notation  $A_{LL}^H$ ,  $A_{LL}^V$ ,  $B_{LR}^H$ ,  $B_{LR}^V$ ,  $C_{LR}^H$ ,  $C_{LR}^V$  is described in section III.  $H(V)$  corresponds to horizontal (vertical) color flow. The amplitude  $P(s,t)$  represents diffractive s-channel scattering via Pomeron exchange when the vacuum quantum numbers can be exchanged in the t-channel. Similarly  $P(t,s)$  is the crossing symmetric pomeron amplitude. The amplitudes  $A_{VV}^V(s,t)$  means that the quantum numbers of a vector meson  $V$  (or any particle on its Regge trajectory) appear in the S-channel and those of  $\bar{V}$  in the t-channel. A definite function of  $s$  and  $t$  is later specified, in sec. VI, for each one of these amplitudes. The notation  $V, \bar{V}, \Sigma, \bar{\Sigma}$  was explained in section II. Thus, in the diagrams two left handed lines  $\leftarrow t$  correspond to  $V$  one left and one right  $\rightarrow t$  correspond to  $\Sigma$ , 4-lefts  $\leftarrow t$  or two scalars  $\leftarrow t$  correspond to  $\bar{V}$  and two lefts plus two rights  $\leftarrow t$  correspond to  $\bar{\Sigma}$ .

Note that we have made an approximation by not distinguishing the various types of preons, thus  $P, \bar{P}$  or  $U_L, \bar{U}_L$  or  $U_L, \bar{U}_L$  or  $F, \bar{F}$  etc. are all represented by  $L$  or  $V$ . Similarly for  $\bar{V}, \Sigma, \bar{\Sigma}$ . Thus, when there is more than one diagram that contributes to a given channel, such as  $A_{VV}^V(s,t)$ , they add up to produce a factor, such as  $2 A_{VV}^V(s,t)$ , etc., as given in the table. Diagrams involving the scalar  $\phi$  (Figs. 2-4) have been represented by  $3 A_{VV}^V$  rather than  $A_{VV}$ , etc. This normalisation allows easier comparison between purely fermionic preon theories and those involving scalar preons. The factor of 3 was chosen on the basis that purely fermionic theories have often 3 diagrams contributing to a given process as opposed to 1 diagram for scalars. Although the overall strength of

$A^{\bar{V}V}$  could be different in various theories we will take it the same for every theory in this paper.

The  $\pm$  that appear in Figs. 3,4 and table 1 depend on whether the right handed preons  $U_R$  or  $D_R$  have the same precolor (+) or opposite precolor (-) compared to  $U_L, D_L$ . The origin of the (-) sign is the following: If  $U_R$  has the opposite precolor of  $U_L$  then the charge conjugate  $(U_L)^C$  [which is equivalent to  $U_R$ ] has the same precolor of  $U_L$ . The preon flavor symmetries would then treat  $U_L$  and  $(U_L)^C$  on the same footing. Then, instead of the left-right spinor structure that appear in eq. (3.1) there would be only left handed spinors with  $(u_L)^C$  and  $(v_L)^C$  replacing  $u_R$  and  $v_R$ , as, e.g.  $\bar{v}_{4L} \gamma^\mu v_{2L}$ , etc. However, we can rewrite those in terms of right handed spinors using

$$\bar{v}_{4L} \gamma^\mu v_{2L}^C = - \bar{v}_{2R} \gamma^\mu v_{4R}$$

thus explaining the (-) sign. Note that this fact can help to distinguish between models quantitatively since the cross sections of section VI are sensitive to this sign.

### V. BETA FUNCTION AMPLITUDES

We have emphasised earlier that we may expect the compositeness amplitudes to describe physical phenomena similar to those seen in low energy strong interaction hadronic physics. Accordingly, the amplitudes  $A^{\bar{V}V}(s,t)$  etc. should display both resonance behaviour as well as Regge behaviour in the  $V(s)$  and  $\bar{V}(t)$  channels respectively. Imitating low energy hadronic physics we may expect an approximate duality principle quantified by a Veneziano type model which is associated with string like confinement phenomena of the preons.

In presenting this model we will assume, for a first estimate and simplicity, that the  $V$  and  $\bar{V}$  trajectories are approximately degenerate. (This could be revised easily following table 1.) Furthermore, since we suggested in eq. 2.1  $\alpha_V = \alpha_{\bar{V}} - 1$ , we may write all our beta function amplitudes in terms of a single trajectory:

$$\alpha(s) = \frac{1}{2} + \alpha' s \quad (1+i/5)$$

An imaginary part  $i\alpha's/5$  has been added to provide a width and move the poles off the real axis. This phenomenological step is needed in practice since we need to perform integrals over a range of  $s$  in order to obtain the proton-proton cross section (see section VIII). With this prescription the width of any resonance satisfies  $\Gamma/M \approx 1/5$ , similar to the rho meson.

Thus, we find that for the correct resonance poles ( $V, \Sigma$  etc.) and Regge behaviour to emerge we may take all amplitudes equal to the same beta function

$$\begin{aligned} A^{\bar{V}V}(s,t) &= A^{\bar{V}V}(s,t) = A^{\bar{V}V}(s,t) \\ &= A^{\bar{V}V}(s,t) = A^{\bar{V}V}(s,t) = A^{\bar{V}V}(s,t) \\ &= B_{st} \end{aligned}$$

where

$$B_{st} = - \frac{1}{4} g_V^2 \alpha' \frac{\Gamma(1-\alpha(s)) \Gamma(1-\alpha(t))}{\Gamma(2-\alpha(s) - \alpha(t))}$$

Note that as the preon scale  $M_V$  goes to infinity ( $\alpha' \rightarrow 0$ ) this amplitude reduces to

$$B_{st} \xrightarrow{\alpha' \rightarrow 0} \frac{\pi}{4} \frac{g_V^2}{2M_V^2},$$

thus becoming equivalent to a 4-Fermi interaction. The first pole in the  $s$ -channel appears at the mass  $M_V^2 (=M_\Sigma^2)$

$$B_{st} \xrightarrow{s \rightarrow M_V^2} \frac{1}{4} \frac{g_V^2}{s - M_V^2 + i M_V^2/5}$$

This could be compared to the  $\rho^0$  pole in  $p\bar{p} \rightarrow n\bar{n}$  in order to estimate the coupling

$$g_V^2 = g_{\rho NN}^2 = 8\pi$$

The asymptotic behaviour reduces to a sum of Regge exchanges. The leading behaviour is

$$B_{st} \xrightarrow{s \rightarrow \infty} - \frac{1}{4} g_V^2 \alpha' (-\alpha(s))^{\alpha(t)-1} \cdot \Gamma(1-\alpha(t))$$

The (-1) in the power is compensated by kinematic factors due to the spinors in eq. 3.1.

To get the correct diffractive scattering in elastic channels we must include the pomeron contribution. This is given as

$$P_s(s,t) = \frac{2\pi g_p^2}{M_V^2} \frac{1+e^{i\pi\alpha_p(t)}}{\cos(\frac{\pi}{2}\alpha_p(t))} (s/M_V^2)^{\alpha_p(t)-1}$$

here the pomeron trajectory has intercept 1:

$$\alpha_p(t) = 1 + \alpha' t.$$

The symbol  $P_t$  in table 1 or in sec. VII implies  $P_t(t,s)$  which is the same amplitude as above with  $s \leftrightarrow t$  interchanged. If this crossing is done naively, the amplitude  $P_t(t,s)$  will violate unitarity bounds when both  $t$  and  $s$  are large. In order to prevent this in our phenomenological estimates we replace  $(s/M_V^2)^{\alpha_p(t)-1}$  by a ratio of gamma functions

$$\Gamma(\frac{1}{2}|\alpha_p(s) + \alpha_p(t)|) / \Gamma(1 + \frac{1}{2}|\alpha_p(s) - \alpha_p(t)|)$$

which has the correct asymptotic behaviour and allows crossing without violating unitarity bounds.

Note that, as  $s \rightarrow \infty$ , the optical theorem relates the coupling  $g_p^2$  to the total cross section

$$\sigma_{Tot}(s) = \frac{1}{s} \text{Im } M(s,t=0) \xrightarrow{s \rightarrow \infty} \frac{2\pi g_p^2}{M_V^2}$$

Therefore, from the geometrical model, eq. (1.3), we estimate  $g_p^2 \approx 9-25$ . We have thus specified a complete quantitative model which should allow us to estimate cross sections at SSC energies which either approach or surpass by many factors the preon scale  $\Lambda_p$ .

### VII. DIFFERENTIAL CROSS SECTIONS

We have now reached the stage of writing down our quark+antiquark  $\rightarrow$  quark+antiquark differential cross sections by combining the reasoning of the previous sections. It has the form

$$\frac{d\sigma}{dt} = \frac{1}{16\pi s^2} |M|^2 \quad (7.1)$$

where  $|M|^2$  depends on the process, as follows:

$u\bar{u} \rightarrow u\bar{u}$ . The cross section is identical for the

reactions  $u\bar{u} \rightarrow u\bar{u}$ ,  $d\bar{d} \rightarrow d\bar{d}$ ,  $s\bar{s} \rightarrow s\bar{s}$ ,  $c\bar{c} \rightarrow c\bar{c}$ ,  $t\bar{t} \rightarrow t\bar{t}$ ,  $b\bar{b} \rightarrow b\bar{b}$ . We obtain

$$|M|^2 = \{u^2 [\frac{4}{9}g^4 (\frac{1}{s^2} - \frac{1}{3st}) + \frac{16}{9}g^2 \text{Re}(x_{B_{st}} + P_s) + \frac{8}{3}x^2 |B_{st}|^2 + \frac{16}{3}x \text{Re}(B_{st}^* P_s) + 2|P_s|^2 + \frac{2}{3} \text{Re}(P_s^* P_t)] + s^2 [\frac{4}{9} \frac{g^4}{t^2} \pm \frac{16}{9}z \frac{g^2}{t} \text{Re}(B_{st}) + 2(y^2 + z^2 + \frac{2}{3}yz) |B_{st}|^2 + \frac{4}{3} (3y+z) \text{Re}(B_{st}^* P_s) + 2|P_s|^2] + \{s \leftrightarrow t\} \quad (7.2)$$

Here the parameters  $x, y, z$  take different values in models (A, B, C, D), described in sec. IV, as follows

$$x = (3, 3, 3, 3); y = (3, 1, 3, 0); z = (0, 2, 0, 3) \quad (7.3)$$

The  $\pm$  is explained in section V.  $g$  is the QCD coupling constant  $g^2/4\pi = 0.1$ .

$u\bar{u} \rightarrow d\bar{d}$ . The expression is identical for  $u\bar{u} \rightarrow d\bar{d}$ ,  $d\bar{d} \rightarrow u\bar{u}$ ,  $c\bar{c} \rightarrow s\bar{s}$ ,  $s\bar{s} \rightarrow c\bar{c}$ ,  $t\bar{t} \rightarrow b\bar{b}$ ,  $b\bar{b} \rightarrow t\bar{t}$ . We have

$$|M|^2 = u^2 \{ \frac{4}{9} \frac{g^4}{s^2} + \frac{16}{9} \frac{g^2}{s} x_H \text{Re}(B_{st}) + 2(x_H^2 + x_V^2 + \frac{2}{3}x_H x_V) |B_{st}|^2 + \frac{4}{3} (3x_V + x_H) \text{Re}(B_{st}^* P_t) + 2|P_t|^2 + 2s^2 (y_H^2 + y_V^2 + 2y_H y_V) |B_{st}|^2 + t^2 \{ \frac{4}{9} \frac{g^4}{s^2} \pm \frac{16}{9} z_H \frac{g^2}{s} \text{Re}(B_{st}) + 2(z_H^2 + z_V^2 + 2z_H z_V) |B_{st}|^2 + \frac{4}{3} (3z_V + z_H) \text{Re}(B_{st}^* P_t) + 2|P_t|^2 \} \quad (7.4)$$

The parameters  $x_{H,V}$ ,  $y_{H,V}$ ,  $z_{H,V}$  differ in models (A, B, C, D):

$$x_H = (0, 2, 0, 3); y_H = (0, 0, 0, 0); z_H = (0, 2, 0, 3) \\ x_V = (3, 1, 3, 0); y_V = (0, 0, 0, 0); z_V = (3, 1, 3, 0) \quad (7.5)$$

$u\bar{u} \rightarrow c\bar{c}$ . The expression is identical for  $u\bar{u} \rightarrow c\bar{c}$ ,  $u\bar{u} \rightarrow t\bar{t}$ ,  $c\bar{c} \rightarrow u\bar{u}$ ,  $c\bar{c} \rightarrow t\bar{t}$ ,  $t\bar{t} \rightarrow u\bar{u}$ ,  $t\bar{t} \rightarrow c\bar{c}$ ,  $d\bar{d} \rightarrow s\bar{s}$ ,  $d\bar{d} \rightarrow b\bar{b}$ ,  $s\bar{s} \rightarrow d\bar{d}$ ,  $s\bar{s} \rightarrow b\bar{b}$ ,  $b\bar{b} \rightarrow d\bar{d}$ ,  $b\bar{b} \rightarrow s\bar{s}$ . It is given by eq. (7.4) except for the value of the parameters:

$$x_H = (2, 2, 3, 0); y_H = (2, 0, 3, 0); z_H = (0, 2, 0, 0) \\ x_V = (1, 1, 0, 3); y_V = (0, 0, 0, 3); z_V = (1, 1, 0, 0) \quad (7.6)$$

$u\bar{u} \rightarrow s\bar{s}$ . The same formula applies to  $u\bar{u} \rightarrow s\bar{s}$ ,  $u\bar{u} \rightarrow b\bar{b}$ ,  $c\bar{c} \rightarrow d\bar{d}$ ,  $c\bar{c} \rightarrow b\bar{b}$ ,  $t\bar{t} \rightarrow d\bar{d}$ ,  $t\bar{t} \rightarrow s\bar{s}$ ,  $d\bar{d} \rightarrow c\bar{c}$ ,  $d\bar{d} \rightarrow t\bar{t}$ ,  $s\bar{s} \rightarrow u\bar{u}$ ,  $s\bar{s} \rightarrow t\bar{t}$ ,  $b\bar{b} \rightarrow u\bar{u}$ ,  $b\bar{b} \rightarrow c\bar{c}$ . It is given by eq. (7.4) with the parameters

$$x_H = (0, 1, 0, 0); y_H = (0, 0, 0, 0); z_H = (0, 1, 0, 0) \\ x_V = (1, 1, 0, 0); y_V = (0, 0, 0, 0); z_V = (1, 1, 0, 0) \quad (7.7)$$

$u\bar{d} \rightarrow u\bar{d}$ . The same formula applies to  $u\bar{d} \rightarrow u\bar{d}$ ,  $c\bar{s} \rightarrow c\bar{s}$ ,  $t\bar{b} \rightarrow t\bar{b}$ ,  $du \rightarrow du$ ,  $cs \rightarrow cs$ ,  $bt \rightarrow bt$ . It is obtained by crossing  $u\bar{u} \rightarrow d\bar{d}$ , eqs. (7.4) and (7.5), by interchanging  $s \leftrightarrow t$ .

$u\bar{s} \rightarrow u\bar{s}$ . The same formula applies to  $u\bar{s} \rightarrow u\bar{s}$ ,  $u\bar{b} \rightarrow u\bar{b}$ ,  $c\bar{d} \rightarrow c\bar{d}$ ,  $c\bar{b} \rightarrow c\bar{b}$ ,  $t\bar{d} \rightarrow t\bar{d}$ ,  $t\bar{s} \rightarrow t\bar{s}$ ,  $d\bar{c} \rightarrow d\bar{c}$ ,

$d\bar{t} \rightarrow d\bar{t}$ ,  $s\bar{u} \rightarrow s\bar{u}$ ,  $s\bar{t} \rightarrow s\bar{t}$ ,  $b\bar{u} \rightarrow b\bar{u}$ ,  $b\bar{c} \rightarrow b\bar{c}$ . It is obtained by crossing from  $u\bar{u} \rightarrow s\bar{s}$ , eqs. (7.4) and (7.7), by interchanging  $s \leftrightarrow t$ .

$u\bar{c} \rightarrow u\bar{c}$ . The same formula applies to  $u\bar{c} \rightarrow u\bar{c}$ ,  $u\bar{t} \rightarrow u\bar{t}$ ,  $c\bar{u} \rightarrow c\bar{u}$ ,  $c\bar{t} \rightarrow c\bar{t}$ ,  $t\bar{u} \rightarrow t\bar{u}$ ,  $t\bar{c} \rightarrow t\bar{c}$ ,  $d\bar{s} \rightarrow d\bar{s}$ ,  $d\bar{b} \rightarrow d\bar{b}$ ,  $s\bar{d} \rightarrow s\bar{d}$ ,  $s\bar{b} \rightarrow s\bar{b}$ ,  $b\bar{d} \rightarrow b\bar{d}$ ,  $b\bar{s} \rightarrow b\bar{s}$ . It is obtained by crossing from  $u\bar{u} \rightarrow c\bar{c}$ , eqs. (7.4) and (7.6), by interchanging  $s \leftrightarrow t$ .

$u\bar{d} \rightarrow d\bar{s}$ . There is no QCD background for this reaction. The same formula applies to  $u\bar{c} \rightarrow d\bar{s}$ ,  $u\bar{t} \rightarrow d\bar{b}$ ,  $c\bar{u} \rightarrow s\bar{d}$ ,  $c\bar{t} \rightarrow s\bar{b}$ ,  $t\bar{u} \rightarrow b\bar{d}$ ,  $t\bar{c} \rightarrow b\bar{s}$ . We have

$$|M|^2 = 2(x_H^2 + x_V^2 + \frac{2}{3}x_H x_V)(u^2 + t^2) |B_{st}|^2 \quad (7.8)$$

where for models (A, B, C, D)

$$x_H = (0, 0, 0, 3); x_V = (2, 0, 3, 0) \quad (7.9)$$

$u\bar{d} \rightarrow c\bar{s}$ . The same formula applies to  $u\bar{d} \rightarrow c\bar{s}$ ,  $u\bar{t} \rightarrow c\bar{b}$ ,  $c\bar{u} \rightarrow s\bar{d}$ ,  $c\bar{t} \rightarrow s\bar{b}$ ,  $t\bar{u} \rightarrow b\bar{d}$ ,  $t\bar{c} \rightarrow b\bar{s}$ . It is obtained by crossing from  $u\bar{c} \rightarrow d\bar{s}$ , eqs. (7.8) and (7.9), by interchanging  $s \leftrightarrow t$ .

### VIII. $pp$ OR $p\bar{p} \rightarrow$ JETS + ANYTHING

The physics of one and two hadronic jets in the final state of  $pp$  or  $p\bar{p}$  scattering is related to the parton cross sections via the formula (see e.g. ref. 7 and references therein)

$$\frac{d\sigma}{dy_1 dy_2 dp_\perp} = \frac{2\pi\tau}{s} p_\perp \sum_{i,j} \{ f_i^a(x_a, M^2) f_j^b(x_b, M^2) \frac{d\hat{\sigma}_{ij}}{dt}(\hat{s}, \hat{t}, \hat{u}) + f_j^a(x_a, M^2) f_i^b(x_b, M^2) \frac{d\hat{\sigma}_{ij}}{dt}(\hat{s}, \hat{u}, \hat{t}) \} / (1 + \delta_{ij}) \quad (8.1)$$

where  $\hat{s} = s\tau$  is the parton-parton subenergy,  $\tau = \frac{4}{s} \text{Cosh}^2 \left[ \frac{1}{2} \ln \left( \frac{y_1 - y_2}{y_1 + y_2} \right) \right]$ ,  $x_a = \sqrt{\tau} \exp(\frac{y_1 + y_2}{2})$ ,  $x_b = \sqrt{\tau} \exp(-\frac{y_1 + y_2}{2})$ .  $\sqrt{s}$  is the proton+(anti)proton total center of mass energy,  $y_1$  and  $y_2$  are the rapidities of the two jets and  $p_\perp$  is their common transverse momentum. Finally,  $\hat{t} = -\hat{s} \sin^2 \theta/2$ ,  $\hat{u} = -\hat{s} \cos^2 \theta/2$  with  $\theta$  = scattering angle in c.m. of partons. The sum  $i, j$  includes all partons, i.e. quarks, antiquarks and gluons.

In ref. 7, EHLQ have made an extensive analysis of parton distributions, QCD background and new physics at the SSC energies. Their treatment of compositeness was limited to energies much smaller than  $\Lambda_p$ , assuming that the SSC energies would not cross the preon threshold. Furthermore, even for such scales they did not include all possible 4-fermi interactions and the effects of compositeness on gluon + quark or gluon + gluon cross sections.

The cross sections given in section VII provide a complete model for composite quark + antiquark and, by crossing, quark + quark scattering. The expected physics: resonances, Regge poles and diffractive scattering is included, unlike ref. 7. Thus, to see the effect of compositeness on jet cross sections we should use the formulas of section VII with  $s, t, u$  replacing  $s, t, u$ . To complete the calculation of the jet cross sections we must also estimate the compositeness corrections to the processes (gluon + quark  $\rightarrow$  gluon + quark), (gluon + gluon  $\rightarrow$  quark + antiquark), (quark + antiquark  $\rightarrow$  gluon + gluon) and gluon + gluon  $\rightarrow$  gluon + gluon. It is important to include these because gluons dominate the parton

distributions at small  $x$ . The calculation of the gluon cross sections is done in a separate publication following the ideas presented in this paper<sup>†</sup>.

Other interesting observables, such as the distribution of two-jet invariant masses is obtained from (8.1) by making appropriate cuts and integrating over rapidities. If the SSC energies reach the resonance region this quantity should show bumps corresponding to the vectors, scalars, excited fermions etc. in our Chew-Frauchi plot of Fig. 1.

Plots of jet cross sections that include the new physics described in this paper will be given elsewhere.

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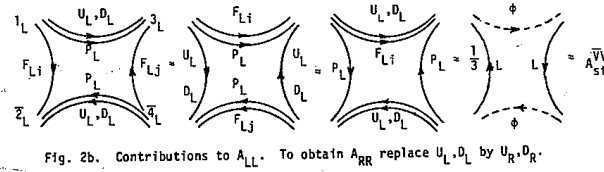
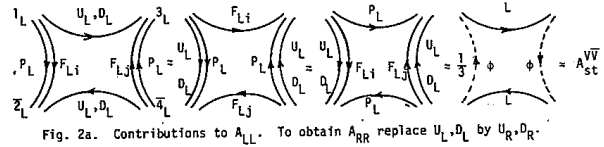


Fig. 2-4. Up, down quantum numbers are carried by U,D. Color or lepton quantum nos are carried by U,D [or by F]. Family quantum nos are carried by F [or by U,D].  $P_L$  compensates for precolor, usually it does not carry the familiar quantum numbers.  $\phi$  stands either for a scalar preon or for a pair of fermionic preons. See models A,B,C,D for distinctions.

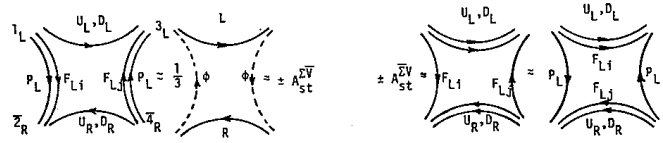


Fig. 3. Contributions to  $B_{LR}$ . To obtain  $B_{RL}$  interchange  $U_L, D_L$  with  $U_R, D_R$ .

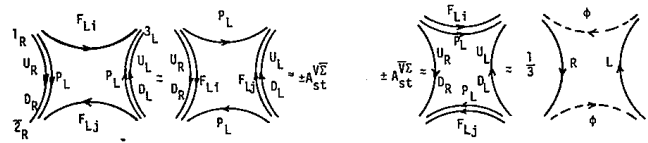


Fig. 4. Contributions to  $C_{LR}$ . To obtain  $C_{RL}$  interchange  $U_L, D_L$  with  $U_R, D_R$ .

Table 1 - Amplitudes corresponding to the preon duality diagrams for models A,B,C,D and for QCD							
Reactions	Model	AMPLITUDES $M(s,t)$					
		$A_H^{LL}$	$A_V^{LL}$	$B_H^{LR}$	$B_V^{LR}$	$C_H^{LR}$	$C_V^{LR}$
$u\bar{u} \rightarrow u\bar{u}$ $d\bar{d} \rightarrow d\bar{d}$ $c\bar{c} \rightarrow c\bar{c}$ $s\bar{s} \rightarrow s\bar{s}$ etc.	QCD	$\frac{1}{2}g^2(1/s-1/3t)$	$\frac{1}{2}g^2(1/t-1/3s)$	$-g^2/6t$	$g^2/2t$	$+g^2/2s$	$-g^2/6s$
	A	$A^{\bar{V}V} + 2A^{\bar{V}V} + P_s$	$2A^{\bar{V}V} + A^{\bar{V}V} + P_t$	$\pm(A^{\bar{E}V} + 2A^{\bar{E}V} + P_s)$	0	0	$\pm(2A^{\bar{V}E} + A^{\bar{V}E} + P_t)$
	B	$A^{\bar{V}V} + 2A^{\bar{V}V} + P_s$	$2A^{\bar{V}V} + A^{\bar{V}V} + P_t$	$\pm A^{\bar{E}V} \pm P_s$	$\pm(A^{\bar{E}V} + A^{\bar{E}V})$	$\pm(A^{\bar{V}E} + A^{\bar{V}E})$	$\pm A^{\bar{V}E} \pm P_t$
	C	$3 A^{\bar{V}V} + P_s$	$3 A^{\bar{V}V} + P_t$	$\pm 3A^{\bar{E}V} \pm P_s$	0	0	$\pm 3A^{\bar{V}E} \pm P_t$
	D	$3 A^{\bar{V}V} + P_s$	$3 A^{\bar{V}V} + P_t$	0 $\pm P_s$	$\pm 3A^{\bar{E}V}$	$\pm 3A^{\bar{V}E}$	0 $\pm P_t$
$u\bar{u} \rightarrow c\bar{c}$ $d\bar{d} \rightarrow s\bar{s}$ $c\bar{c} \rightarrow u\bar{u}$ $s\bar{s} \rightarrow d\bar{d}$ etc.	QCD	$g^2/2s$	$-g^2/6s$	0	0	$+g^2/2s$	$-g^2/6s$
	A	$A^{\bar{V}V} + A^{\bar{V}V}$	$A^{\bar{V}V} + P_t$	$\pm A^{\bar{E}V} + A^{\bar{E}V}$	0	0	$\pm A^{\bar{V}E} \pm P_t$
	B	$A^{\bar{V}V} + A^{\bar{V}V}$	$A^{\bar{V}V} + P_t$	0	0	$\pm(A^{\bar{V}E} + A^{\bar{V}E})$	$\pm A^{\bar{V}E} \pm P_t$
	C	$3 A^{\bar{V}V}$	$P_t$	$\pm 3 A^{\bar{E}V}$	0	0	$\pm P_t$
	D	0	$3 A^{\bar{V}V} + P_t$	0	$\pm 3 A^{\bar{E}V}$	0	$\pm P_t$
$u\bar{u} \rightarrow d\bar{d}$ $d\bar{d} \rightarrow u\bar{u}$ $c\bar{c} \rightarrow s\bar{s}$ $s\bar{s} \rightarrow c\bar{c}$ etc.	QCD	$g^2/2s$	$-g^2/6s$	0	0	$+g^2/2s$	$-g^2/6s$
	A	0	$2A^{\bar{V}V} + A^{\bar{V}V} + P_t$	0	0	0	$\pm(2A^{\bar{V}E} + A^{\bar{V}E}) \pm P_t$
	B	$A^{\bar{V}V} + A^{\bar{V}V}$	$A^{\bar{V}V} + P_t$	0	0	$\pm(A^{\bar{V}E} + A^{\bar{V}E})$	$\pm A^{\bar{V}E} \pm P_t$
	C	0	$3 A^{\bar{V}V} + P_t$	0	0	0	$\pm 3A^{\bar{V}E} \pm P_t$
	D	$3 A^{\bar{V}V}$	0 $+ P_t$	0	0	$\pm 3A^{\bar{V}E}$	0 $\pm P_t$
$u\bar{u} \rightarrow s\bar{s}$ $d\bar{d} \rightarrow c\bar{c}$ $c\bar{c} \rightarrow d\bar{d}$ $s\bar{s} \rightarrow u\bar{u}$ etc.	QCD	$g^2/2s$	$-g^2/6s$	0	0	$+g^2/2s$	$-g^2/6s$
	A	0	$A^{\bar{V}V} + P_t$	0	0	0	$\pm A^{\bar{V}E} \pm P_t$
	B	$A^{\bar{V}V}$	$A^{\bar{V}V} + P_t$	0	0	$\pm A^{\bar{V}E}$	$\pm A^{\bar{V}E} \pm P_t$
	C	0	$P_t$	0	0	0	$\pm P_t$
	D	0	$P_t$	0	0	0	$\pm P_t$
$u\bar{d} \rightarrow u\bar{d}$ $d\bar{u} \rightarrow d\bar{u}$ $c\bar{s} \rightarrow c\bar{s}$ $s\bar{c} \rightarrow s\bar{c}$ etc.	QCD	$-g^2/6t$	$g^2/2t$	$-g^2/6t$	$g^2/2t$	0	0
	A	$A^{\bar{V}V} + 2A^{\bar{V}V} + P_s$	0	$\pm(A^{\bar{E}V} + 2A^{\bar{E}V}) \pm P_s$	0	0	0
	B	$A^{\bar{V}V} + P_s$	$A^{\bar{V}V} + A^{\bar{V}V}$	$\pm A^{\bar{E}V} \pm P_s$	$\pm(A^{\bar{E}V} + A^{\bar{E}V})$	0	0
	C	$3 A^{\bar{V}V} + P_s$	0	$\pm 3 A^{\bar{E}V} \pm P_s$	0	0	0
	D	0 $+ P_s$	$3 A^{\bar{V}V}$	0 $\pm P_s$	$\pm 3A^{\bar{E}V}$	0	0
$u\bar{s} \rightarrow u\bar{s}$ $s\bar{u} \rightarrow s\bar{u}$ $c\bar{d} \rightarrow c\bar{d}$ $d\bar{c} \rightarrow d\bar{c}$ etc.	QCD	$-g^2/6t$	$g^2/2t$	$-g^2/6t$	$g^2/2t$	0	0
	A	$A^{\bar{V}V} + P_s$	0	$\pm(A^{\bar{E}V} + P_s)$	0	0	0
	B	$A^{\bar{V}V} + P_s$	$A^{\bar{V}V}$	$\pm A^{\bar{E}V} \pm P_s$	$\pm A^{\bar{E}V}$	0	0
	C	$P_s$	0	$\pm P_s$	0	0	0
	D	$P_s$	0	$\pm P_s$	0	0	0
$u\bar{c} \rightarrow u\bar{c}$ $d\bar{s} \rightarrow d\bar{s}$ $c\bar{u} \rightarrow c\bar{u}$ $s\bar{d} \rightarrow s\bar{d}$ etc.	QCD	$-g^2/6t$	$g^2/2t$	$-g^2/6t$	$g^2/2t$	0	0
	A	$A^{\bar{V}V} + P_s$	$A^{\bar{V}V} + A^{\bar{V}V}$	$\pm A^{\bar{E}V} \pm P_s$	0	0	$\pm(A^{\bar{V}E} + A^{\bar{V}E})$
	B	$A^{\bar{V}V} + P_s$	$A^{\bar{V}V} + A^{\bar{V}V}$	$\pm A^{\bar{E}V} \pm P_s$	$\pm(A^{\bar{E}V} + A^{\bar{E}V})$	0	0
	C	0 $+ P_s$	$3 A^{\bar{V}V}$	0 $\pm P_s$	0	0	$\pm 3 A^{\bar{V}E}$
	D	$3 A^{\bar{V}V} + P_s$	0	0 $\pm P_s$	0	$\pm 3 A^{\bar{V}E}$	0
$u\bar{c} \rightarrow d\bar{s}$ $c\bar{u} \rightarrow s\bar{d}$ etc.	QCD	0	0	0	0	0	0
	A	0	$A^{\bar{V}V} + A^{\bar{V}V}$	0	0	0	$\pm(A^{\bar{V}E} + A^{\bar{V}E})$
	B	0	0	0	0	0	0
	C	0	$3 A^{\bar{V}V}$	0	0	0	$\pm 3 A^{\bar{V}E}$
	D	$3 A^{\bar{V}V}$	0	0	0	$\pm 3 A^{\bar{V}E}$	0
$u\bar{d} \rightarrow c\bar{s}$ $d\bar{u} \rightarrow s\bar{c}$ etc.	QCD	0	0	0	0	0	0
	A	$A^{\bar{V}V} + A^{\bar{V}V}$	0	$\pm(A^{\bar{E}V} + A^{\bar{E}V})$	0	0	0
	B	0	0	0	0	0	0
	C	$3 A^{\bar{V}V}$	0	$\pm 3 A^{\bar{E}V}$	0	0	0
	D	0	$3 A^{\bar{V}V}$	0	$\pm 3 A^{\bar{E}V}$	0	0

PROBING FOR PREON STRUCTURE VIA GLUONS

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Summary

Gluons form an important fraction of the partons at small  $x$  in  $pp$  scattering at SSC energies ( $\approx 40$  TeV). Therefore, gluon reactions at the SSC may be expected to yield important signals for compositeness, if the preon scale is a few TeV. Here we develop a quantitative method for estimating many gluon scattering processes. Some of our estimates are model independent. We also propose explicit formulas for various scattering amplitudes based on a Veneziano-type beta function model that exhibits resonances and Regge behavior. Many interesting spectacular signatures are suggested in the resonance region, where massive vector bosons and/or excited and exotic quarks and leptons can be produced.

Introduction

If the preon scale can be reached or surpassed in the parton-parton center of mass at the SSC energies, we expect to find many signals of new physics indicating compositeness of quarks and/or leptons.

In the following, we shall use the mass,  $M_V \gtrsim 1$  TeV, of the first heavy composite vector meson (analog of  $\rho$ ) as a convenient characteristic scale of compositeness. The existing bounds on the preon scale and constraints that must be satisfied in models consistent with  $M_V$  of order 1 TeV are given in ref. 1.

In order to make quantitative estimates of the effects of compositeness and understand its characteristic signals, we must provide parton-parton scattering amplitudes which include the effects of the underlying strong precolor interactions. In analogy to ordinary strong interactions we need to account for massive ( $\gtrsim M_V$ ) resonances, Regge behavior and diffractive scattering. Quantative methods which are useful for this analysis were given in ref. 2. In particular, a spectrum of heavy composites lying on Regge trajectories was introduced, and a model for quark-(anti)quark scattering amplitudes was developed. These amplitudes were based on a string analogy (precolor flux tube) or Veneziano-type formulas (beta functions) which correspond to duality diagrams for preons.

Here we follow the approach of ref. 2 to take into account the contribution of gluons to the partons and jets in the context of compositeness: Gluons are important because, among the wee partons (small  $x$ ) which dominate the parton distributions, they make the largest contribution to the pure QCD background<sup>3</sup>. We note that the role of gluons relative to composite colored quarks and color neutral leptons is analogous to the role of the photon relative to composite charged and neutral hadrons. This analogy helps a great deal to develop intuition and will guide us not only qualitatively but also quantitatively as shown below. In the same vein we introduce the vector meson dominance model to discuss spectacular signals of jets and leptons with energies of order  $M_V$  which are expected in the final states of  $pp$  collisions.

Gluon Cross Sections

The parton differential cross sections for  $a+b \rightarrow c+d$ , where at least two of the partons are gluons, can be expressed in the general form

$$\frac{d\sigma}{dt} = - \frac{\pi \alpha_{QCD}^2}{s^2} |M(s, t, u)|^2 \quad (1)$$

in terms of the Mandelstam variables  $s, t, u$  for the parton reaction. To obtain the cross sections for  $p+p \rightarrow$  jets + anything, one must fold these, along with purely quark cross sections,<sup>2</sup> with parton distributions following the prescription of the parton model<sup>3</sup>. In what follows, we discuss  $|M|^2$  for each basic process with explicit modifications to the QCD results taken into account.

$gg \rightarrow q\bar{q}$  The preon duality diagrams that contribute to this process are depicted in Fig. 1, where the gluon is attached to the preon that carries color. The kinematic factors due to the spins of partons are identical to those appearing in the QCD amplitudes for elementary gluons and quarks. On the other hand, the pure QCD invariant amplitudes,<sup>3</sup> to lowest order, consist simply of poles  $1/s, 1/t, 1/u$ , corresponding to the propagators of gluons or quarks. These must be replaced by composite amplitudes that have poles or Regge exchanges in the  $s, t, u$  channels as indicated by the duality diagrams. Furthermore, as  $M_V \rightarrow \infty$ , the composite amplitudes must reduce to the pure QCD amplitudes.

Thus, in a model-independent way we can write

$$|M|^2 = \frac{3}{8} \left\{ (t^2 + u^2) \left| \frac{A_s}{s} \right|^2 - \frac{4}{9} t u \left| \frac{A_{st}^{VF} + P_{ts}^t}{s t} \right|^2 - \frac{4}{9} t u \left| \frac{A_{su}^{VF} + P_{us}^u}{s u} \right|^2 \right\} \quad (2)$$

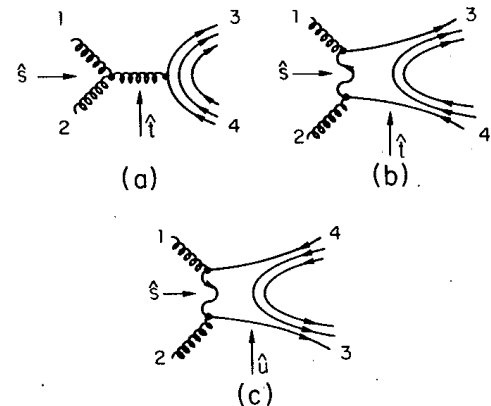


Figure 1  
 Preon duality diagrams for the  $gg + q\bar{q}$  process.

where the three terms correspond to Figs. 1a, b, and c respectively. No interference terms between the diagrams appear because they are proportional to  $s+t+u=0$  in the zero quark mass limit. Here  $A_s$  is a form factor for the vertex  $gqq$  which must reduce to 1 for a gluon on mass shell ( $s=0$ ) and must have power asymptotic falloff as  $s \rightarrow \infty$ , in analogy to the electromagnetic form factors of hadrons. Similarly,  $A_{st}^{VF}$  is an amplitude with resonance poles or Regge exchanges in the  $s$ -channel ( $V$ =vector) or the  $t$ (0)-channel ( $F$ =fermion). In the limit  $M_V \rightarrow \infty$  this amplitude must reduce to a simple  $t$ (0)-channel pole,  $1/t(1/0)$ , corresponding to quark exchange in pure QCD. Also, as  $s \rightarrow \infty$  it must reduce to a Regge exchange dominated by the quark Regge trajectory  $\alpha_F$ . The function  $P_{st}^u(P_{st}^s)$  is the Pomeron contribution. Its presence will be better understood when we discuss  $gq \rightarrow gq$  below.

As in ref. 2, we propose to construct these functions from ratios of gamma functions:

$$A_s = \frac{1}{\sqrt{\pi}} \frac{\Gamma[1-\alpha^V(s)]}{\Gamma[5/2-\alpha^V(s)]} \quad (3a)$$

$$A_{st}^{VF} = -\alpha'(1+i\Gamma_V/M_V) \frac{\Gamma[1-\alpha^V(s)] \Gamma[1/2-\alpha^F(t)]}{\Gamma[3/2-\alpha^V(s)-\alpha^F(t)]} \quad (3b)$$

where

$$\begin{aligned} \alpha^V(s) &= 1/2 + \alpha's(1+i\Gamma_V/M_V) \\ \alpha^F(t) &= 1/2 + \alpha't(1+i\Gamma_F/M_F) \end{aligned} \quad (4)$$

Thus these amplitudes exhibit resonances that lie on Regge trajectories whose intercepts are chosen by analogy to hadrons ( $V \sim \rho$ ) and by taking unbroken chiral symmetry into account ( $\alpha^F(0)=1/2$ ). The slope  $\alpha'=(2M_V^2)^{-1}$  is required so that  $\text{Re}[\alpha'(M_V^2)]=1$ . An imaginary part  $i\alpha'\Gamma/M$  is added to provide a width. We shall fix it such that  $\Gamma/M=1/5$  for all resonances. The overall constants are chosen to reflect the correct QCD normalization as  $M_V \rightarrow \infty$ . The gamma functions in the denominators provide the correct asymptotic behavior as  $s \rightarrow \infty$  in lieu of kinematic factors in Eq. (2). The  $s^{-3/2}$  power fall-off of  $A_s$  could be increased by increasing the  $5/2$  in the gamma function; however,  $5/2$  should not be replaced by an integer, since this would cancel the poles of  $A_s$ , except for the first few.

$q\bar{q} \rightarrow gq$  This process is the inverse of  $gq \rightarrow q\bar{q}$ . Hence we have the same amplitudes, but the color factor is different in the initial state:

$$\begin{aligned} |M|^2 &= \frac{8}{3} \left\{ (t^2+u^2) \left| \frac{A_s}{s} \right|^2 - \frac{4}{9} t u \left| A_{st}^{VF} + P_{st}^t \right|^2 \right. \\ &\quad \left. - \frac{4}{9} t u \left| A_{su}^{VF} + P_{su}^u \right|^2 \right\} \end{aligned} \quad (5)$$

$gq \rightarrow gq$  This process is obtained from  $gq \rightarrow q\bar{q}$  by crossing and changing the color factor in the initial state:

$$\begin{aligned} |M|^2 &= (s^2+u^2) \left| \frac{A_t}{t} \right|^2 - \frac{4}{9} s u \left| A_{ts}^{VF} + P_{ts}^s \right|^2 \\ &\quad - \frac{4}{9} s u \left| A_{tu}^{VF} + P_{tu}^u \right|^2 \end{aligned} \quad (6)$$

Here, in a somewhat ad-hoc fashion, we have added the

Pomeron exchange in the  $t$ -channel  $P_{st}^s, P_{st}^u$ . We choose this function as in ref. 2:

$$P_{st}^s = \frac{2\pi g_P^2}{M_V^2} \frac{1+e^{i\pi\alpha_P(t)}}{\cos[\frac{\pi}{2}\alpha_P(t)]} \frac{\Gamma[\frac{1}{2}|\alpha_P(s)+\alpha_P(t)|]}{\Gamma[1+\frac{1}{2}|\alpha_P(s)-\alpha_P(t)|]} \quad (7)$$

where

$$\alpha_P(t) = 1+\alpha't, \quad g_P^2 = 9-25 \quad (8)$$

The asymptotic ratio of the  $\Gamma$  functions is

$$(s/4M_V^2)^{\alpha_P(t)-1}$$

This form was chosen so that the unitarity bounds are not violated in crossing to the reaction  $gq \rightarrow q\bar{q}$  in Eq. (2) and (5).

$gg \rightarrow gg$  Because we now have 4 rather than 2 gluons, compositeness contributions to this process must be suppressed by a factor of  $\alpha_{QCD}^2$  relative to the reactions considered above. Therefore, to lowest order the pure QCD contribution of ref. 3 is adequate for a reasonable estimate.

#### Rescaling from Hadronic Cross Sections

There are certain reactions among gluons and composite quarks whose diagrams are essentially in one-to-one correspondence to reactions among photons and composite protons. Using this correspondence, we may estimate the cross sections by a simple rescaling prescription applied to the  $\gamma p$  cross sections, as suggested below. As examples, we will discuss the total cross sections for  $gq \rightarrow$  all composites, and  $gq \rightarrow$  composite vector meson + composite fermion.

$\sigma_{tot}(gq)$  According to the optical theorem the total cross section is given by

$$\sigma_{tot}(gq) = \frac{1}{s} \text{Im} A(gq \rightarrow gq) \quad (9)$$

In lowest order QCD, the triple gluon vertex does not contribute to the imaginary part of the elastic amplitude, so that this process is analogous to  $\gamma p \rightarrow$  all hadrons. We can then estimate the new cross section by using the experimental data on  $\sigma_{tot}(\gamma p)$  and applying the following rescaling formula

$$\sigma_{tot}^{gq}(s) = \left( \frac{2\alpha_{QCD}}{9\alpha} \right) \frac{1}{s} [P_{CM}(s') \sqrt{s'} \sigma_{tot}^{\gamma p}(s')] \quad (10)$$

where the color factor  $(2\alpha_{QCD}/9\alpha)=3$  takes into account color averaging and substitutes the coupling of the gluon instead of the photon. Here  $P_{CM}(s')$  is the center of mass momentum of  $\gamma p$ , and  $s$  is the CM energy squared of  $gq$ . The dimensionless quantity in the square brackets is evaluated at  $s'$  rather than  $s$ , where

$$s' = \frac{m^2}{M_V^2} (s + 2M_V^2) \quad (11)$$

The factor  $m^2/M_V^2$  allows us to rescale to the preon scale, instead of the QCD scale. The translation of  $s$  by  $(m^2/M_V^2)(2M_V^2) = 2m^2 \approx m_{\text{proton}}^2$  takes into account the fact that chiral symmetry is exact in the preon theory (massless quarks). This is equivalent to shifting the proton Regge trajectory from intercept  $\approx -1/2$  to intercept  $\approx 1/2$ .

Plots for the total cross section  $\sigma_{tot}(gq)$  as a function of  $\sqrt{s}$ , at different values of  $M_V$ , are easily



generated from known  $\gamma p$  data but will not be given here for lack of space. At small  $s$  there are, of course, peaks corresponding to fermions on the same trajectory as the quark (see ref. 2) similar to the peaks for  $N^*$ ,  $\Delta$ , etc., in  $\gamma p$ . In the resonance region, apart from peaks, the cross section drops from  $\approx 1.0$   $(1\text{TeV}/M_V)^2 \text{nb}$  to  $0.2$   $(1\text{TeV}/M_V)^2 \text{nb}$ . At larger values of  $\sqrt{s} (> 10 M_V)$  the cross section settles to almost a constant (but slightly rising) value of  $0.1$   $(1\text{TeV}/M_V)^2 \text{nb}$ .

$g+q \rightarrow V+q(l)$  In this process the final state may consist of either a quark plus an octet/singlet vector meson, or a lepton plus a lepto-quark vector meson. (See the next section for more details.) This is analogous to photoproduction of vector mesons such as  $\gamma+p \rightarrow p$ . By the scaling arguments given above we may write

$$\left[ \frac{d\sigma}{dt}(s, t, u) \right]_{gq \rightarrow V+g(l)} = \left( \frac{2\alpha_{\text{QCD}}^2}{9\alpha^2} \right) \frac{1}{s^2} \times [P_{\text{CM}}(s') s' \frac{d\sigma}{dt}(s', t', u')]_{\gamma p \rightarrow p^0 p} \quad (12)$$

with

$$s' = \frac{m^2}{M_V^2} (s + 2M_V^2); \quad t' = \frac{m^2}{M_V^2} t; \quad u' = \frac{m^2}{M_V^2} (u + 2M_V^2) \quad (13)$$

Here  $t$  is not translated, since in the  $t$ -channel we expect the quantum numbers of vector mesons, not fermions. We have assumed that the intercepts of vector meson trajectories are not affected appreciably by chiral symmetry (see ref. 2). Note that  $s+t+u=M_V^2$  is consistent with  $s'+t'+u'=m^2+2m_p^2$ , so that the parametrization used for  $\gamma p \rightarrow p^0 p$ , i.e.  $(s', t')$  or  $(s', u')$  or  $(u', t')$  or  $(s', t', u')$  is not crucial to the rescaling. The rescaling could therefore be done from a theoretical expression or available photoproduction data for the differential cross section. Similar remarks apply to the production of heavy fermions instead of the quarks or leptons, if for example we compare the powers  $g+q \rightarrow V+(\Delta, q^*)$  to  $\gamma+p \rightarrow p^0+(\Delta, q^*)$ .

#### Vector Meson Dominance

Vector meson production is also conveniently described by the Vector Meson Dominance model, provided the reaction takes place close enough to threshold, so that the preon quantum fluctuations are sufficiently "frozen" during the time of passage of the gluon. In this picture the gluon couples directly to the colored-octet preon bound state  $V_8$  with coupling  $\gamma_V$ , in analogy to the  $\rho$ - $\gamma$  mixing parameter  $\gamma_\rho$ .

Two duality diagrams of special interest for vector meson production are shown in Fig. 2, where the colored preon, labeled C, is explicitly indicated. In Fig. 2a the reactions

$$g(V_8)+q \rightarrow (V_8, V_1) + (q, \Delta_q, q^*) \quad (14a)$$

or

$$g(V_8) + q \rightarrow V_3 + (\ell, \Delta_\ell, \ell^*) \quad (14b)$$

occur depending on whether the X preon exchanged between the vector meson and fermion carries color or not. In the above reactions the  $\Delta_q$  or  $q^*$  Regge trajectory is exchanged in the  $s$ -channel with a  $V_8$  or  $V_1$  trajectory exchanged in the  $t$ -channel for (14a) and a  $V_3$  lepto-quark trajectory exchanged in reaction (14b). In Fig. 2b, reactions

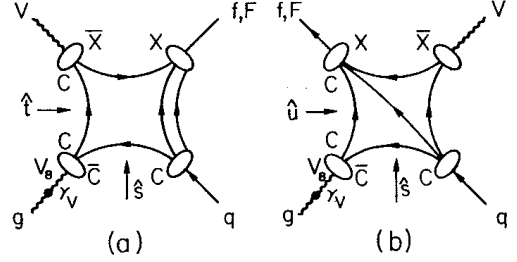


Figure 2  
Preon duality diagrams for the  $gq \rightarrow V(f, F)$  reaction of (14) and (15).

$$g(V_8) + q \rightarrow (q, \Delta_q, q^*) + V_1' \quad (15a)$$

$$g(V_8) + q \rightarrow (Q_8, Q_1) + V_3 \quad (15b)$$

or

$$g(V_8) + q \rightarrow (Q_6, Q_3) + V_3 \quad (15c)$$

take place, again dependent upon the type of X preon exchanged. The corresponding Regge exchanges are  $\Delta_q$  and  $q^*$  trajectories in the  $s$ -channel as well as the  $Q$ -channel for (15a), while exotic quark trajectories  $Q_8$  and  $Q_1$  or  $Q_6$  and  $Q_3$  occur in the  $Q$ -channel for (15b). All these are model dependent.

If the colored octet meson  $V_8$  in (14a) is only virtual and couples with strength  $\gamma_V$  directly to a gluon, reaction (14a) with light quark emission is just that discussed earlier for  $gq+gq$ . In all other cases, massive vector meson production occurs followed by one of the decay channels listed below:

$$V_8 \rightarrow q\bar{q} \quad (16a)$$

$$V_1' \rightarrow q\bar{q}, \ell\bar{\ell} \quad (16b)$$

$$V_3 \rightarrow q\bar{q} \quad (16c)$$

#### Some Spectacular Signatures

Aside from the large deviations (magnitude, bumps, etc.) from QCD predictions expected in the pp or pp cross sections as a result of the preon structure discussed earlier and in ref. 2, some rather spectacular qualitative signature for compositeness arise with the production and decay of heavy fermions and/or vector bosons when  $\sqrt{s} \geq M_V \sim (3-5)\Lambda_{\text{HC}}$ . In particular, we list the following:

- 1) Decay (16a) of  $V_8$  into quark pairs leading to two quark jets nearly back-to-back with an invariant mass that resonates at  $M_{V_8} \approx M_V$ . The momentum of each jet will be unusually large, roughly  $M_V/2$ .
- 2) Decay (16b) of  $V_1'$  into high momentum ( $\sim M_V/2$ ) quark or lepton pairs nearly back-to-back and in the ratio 3:1 with invariant mass resonating at  $M_{V_1'} \approx M_V/2$ . In general, the fermion pairs produced will belong to the same generation, but this need not be the case for  $V_1'$  in (15a), e.g., if the color singlet boson is a bound state of preon pairs which carry the generation label. In this case,  $V_1'$  corresponds to one of the "horizontal" bosons discussed in ref. 4. In a composite model the mass of any horizontal boson is expected to be approximately  $M_V$ .

3) Decay (16c) of the  $V_3$  lepto-quark into a quark jet and a lepton nearly back-to-back with momentum  $M_V/2$  and invariant mass resonating at  $M_{V3} = M_V$ .

4) The above decays taken together with the production channels (14) and (15) result in three high momentum quark jets or a lepton pair and a quark jet with invariant masses peaked at the masses of the  $\Delta$  or  $q^*$  resonances,  $M_{\Delta} \approx M_{q^*} \approx \sqrt{2}M_V$ . The lepton pair reaction will then yield a large resonance contribution on top of the standard Drell-Yan background as discussed in ref. 5.

5) Production of excited quarks ( $\Delta_q, q^*$ ) and leptons ( $\Delta_l, l^*$ ) with masses  $\sim \sqrt{2}M_V$ , as well as possibly some fermions with exotic quantum numbers, with decays into light fermions and heavy vector mesons.

6) Multiquark and multilepton production through multiperipheral graphs with Regge trajectories exchanged in the  $t$ -channel. Since the fermion and boson trajectories are nearly degenerate, the light quarks and leptons can be emitted directly from the Regge exchange, without the production and decay of massive vector bosons. Hence a spray of quarks and leptons should signal the crossing of the preon threshold. The lepton-to-quark ratio should be just slightly smaller than 1/3 due to the unbalanced quark in the  $gq$  reaction.

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# CAN THE PREON SCALE BE SMALL?

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## SUMMARY

The preon scale  $\Lambda_p$  is bounded from below by rare or unobserved processes and from above by the cosmological abundance of stable heavy composites. On the other hand composite models can be tested by the Superconducting Super Collider (SSC) or by low energy precision experiments only if  $\Lambda_p$  is allowed to be at most 5-10 TeV. In search of such models we re-examine some conditions that must be fulfilled if  $\Lambda_p$  is small, and point out the possibility of certain mechanisms that could avoid the dangerous rare processes. In addition, certain properties of exotic composite particles, their possible role in breaking the electroweak symmetry and in producing observable signals beyond the standard model are also discussed.

### 1. LOW ENERGY CONSEQUENCES OF PREON SYMMETRIES

The structure of a preon theory is similar to QCD in many ways. Quarks are confined by color forces at a scale  $\Lambda_{QCD}$  to form hadrons; preons are confined by precolor forces at the scale  $\Lambda_p$  to form composite quarks and leptons (and maybe some exotics). Like the quarks, preons come in several (pre) flavors that define the preonic symmetries. The major difference from QCD is that the preonic chiral symmetries must remain unbroken in the vacuum<sup>1</sup>. They are slightly broken when perturbed by another force which is small compared to precolor. This generates the small masses,  $m \ll \Lambda_p$ , of quarks and leptons.

At low energies ( $E \ll \Lambda_p$ ), in analogy to the sigma model that follows from QCD, we may write an effective theory (see e.g. ref. 2) that describes the low lying composite states of the preon theory. This must have the form

$$L_{eff} = L(\text{standard}) + L(\text{non-renormalizable}).$$

The symmetry structure of  $L_{eff}$  is dictated at the scale  $\Lambda_p$  where the bound states form. At  $\Lambda_p$  all known forces (including QCD) are small compared to the confining precolor interactions. It is therefore useful to consider the limit in which all forces except for precolor is turned off. The fully conserved preonic flavor symmetries  $G_F$  that show up in this limit govern the classification of all composite states. These may include

- (i) 3 or more generations of massless quarks and leptons
- (ii) Massless exotics (color, weak isospin, charge)
- (iii) Heavy composites  $m \geq \Lambda_p$  classified in irreducible representations  $\{r\}$  of  $G_F$ .

Only the states (i) and (ii) are included in  $L_{eff}$ . At energies  $E \geq \Lambda_p$  the states (iii) are also considered.

The symmetries  $G_F$  also govern the structure of the 4-fermi and other non-renormalizable interactions that appear in the effective low energy Lagrangian.  $SU(3) \times SU(2) \times U(1)$  must be a subgroup of  $G_F$ . It is gauged. The classification and structure of interactions provided by  $G_F$  are only slightly changed

when QCD, electroweak or other mass generating interactions are turned on (however, the model should have the property that these symmetry breaking interactions must not mediate undesirable levels of neutral  $\Delta S = 1, 2$  or other reactions that may be introduced via mass generation and "Cabibbo" mixing).

The important role of the 4-fermi interactions for testing compositeness at low energies was first discussed in Ref. 2 and later in the 82 workshop<sup>3</sup> and other articles<sup>4</sup>. In the effective theory the 4-fermi interactions are assumed to have the strength  $\lambda^2/2\Lambda_p^2$ . If they mediate a rare or unobserved process then  $\Lambda_p$  may be required to be large. Here are some of the bounds on  $\Lambda_p$  taken from Ref. 2.

Process	Limit on $\Lambda_p$
Proton decay	$\Lambda_p > \lambda \times 10^{13}$ TeV
$K^0 - \bar{K}^0$ mixing	$\Lambda_p > \lambda \times 400$ TeV
$D^0 - \bar{D}^0$ mixing	$\Lambda_p > \lambda \times 50$ TeV
$K^+ \rightarrow \pi^+ \mu^+ e$	$\Lambda_p > \lambda \times 30$ TeV
$K_L \rightarrow \mu^+ e$	$\Lambda_p > \lambda \times 25$ TeV

Naively the magnitude of  $\lambda$  (unless  $\lambda=0$  because of symmetry) is estimated to be of order 1 by analogy<sup>2,5</sup> to QCD. [Note different definitions of the scale  $\Lambda$  used by others authors<sup>3,4</sup>.] We see that from the point of view of the SSC the most interesting models are those with enough symmetries that require  $\lambda=0$  to suppress each one of the above (and similar rare) processes.

It is remarkable that many of the proposed preon models can be banned from the TeV regime (i.e.  $\Lambda_p \gg \text{few TeV}$ ) thanks to the existence of the few precision measurements listed above. There are proposed experiments to improve the limits of K-decays. The impact of future experiments on  $\Lambda_p$  can be estimated by noting that the dependence of the decay rates on  $\Lambda_p$  is quartic<sup>2</sup>:  $\Gamma(K\text{-decay}) \sim (1/\Lambda_p)^4$ .

It is not difficult to find models<sup>2</sup> with symmetries that suppress the 4-fermi and higher dimension interactions (i.e.  $\lambda=0$  identically) that mediate (1) proton decay, (2)  $K^0 - \bar{K}^0$  mixing and (3)  $D^0 - \bar{D}^0$  mixing. The criteria to eliminate these are as follows<sup>2</sup>: (1) Baryon number must be one of the conserved quantum numbers in the form of a  $U(1)$  embedded in  $G_F$ . (2) There must be no symmetry embedded in  $G_F$  that can transform the left-right components of the composite strange quark when written in the form  $(s_L, s_R)$ , where  $s_L$  is the charge conjugate of  $s_R$ . This may be assured by requiring  $s_L, s_R$  to belong to distinct representations of the (sub)group(s) of  $G_F$ . (3) There must be no symmetry in  $G_F$  that can mix the left-right components of the composite charmed quark in the form  $(c_L, c_R)$  where  $c_L$  is the charge conjugate of  $c_R$ . Again, this may be assured by requiring  $c_L, c_R$  to belong to distinct representations of the (sub)group(s) of  $G_F$ . [The following provides an undesirable example: If the Georgi-Glashow  $SU(5)$  is embedded in  $G_F$  then the 10 contains  $(c_L, c_R)$  and they can mix via  $F_6$  a generator of  $SU(5) \subset G_F$ . If this happens then  $D^0 - \bar{D}^0$  mixing will occur via the 4-fermi interactions, and will require  $\Lambda_p > 50$  TeV]. These criteria are compatible with the symmetry structure of the standard model based on  $SU(3) \times SU(2) \times U(1)$  which is expected to emerge as the low energy limit of the preon theory.

However, as pointed out in ref. 2, the case of K-decays is more delicate because, unlike the other processes,  $\lambda=0$  may not be so easy to achieve by symmetries which classify the quarks and leptons together in repetitive families.  $K \rightarrow \pi \mu e$  or  $K_s \rightarrow \mu e$  can be eliminated by symmetries only by deviating from the intuitive classification of families suggested by the standard model as described below.

The mass spectrum of quarks and leptons together with  $SU(3) \times SU(2) \times U(1)$  anomaly cancellation arguments within the standard model have led to the notion that a single family contains both quarks and leptons and that there exists at least 3 families of increasing masses. A complete family contains 16 or 15 fermion degrees of freedom. [The structure of Grand Unified Theories reinforces the notion that quarks and leptons belong together in one family.] The repetition as replicas of the first one is not explained in theories of elementary quarks and leptons. In composite models it has been suggested that the repetition is required at least in certain classes of models, due to anomaly cancellation of precolor in the underlying preon theory, thus connecting the existence of families to underlying dynamics.

In the limit of zero gauge couplings for  $SU(3) \times SU(2) \times U(1)$ , and absence of a Higgs, the standard model shows a big symmetry:  $SU(48)$  (or  $SU(45) \rightarrow 15$  per family) corresponding to 48 (or 45) left handed free fermions. Thus, in the absence of the gauge couplings and masses in the standard model the family structure is completely washed out. This is an accident simply because  $L$  (standard) is quadratic in the fermions. However, in a composite model, if there is a family structure, it will show up in the structure of the 4-fermi and other non-renormalizable interactions. Thus the preonic symmetry  $G_F$  that provides a family structure must be a subgroup of  $SU(48)$  or a larger group if there are more families. There are, of course, many possibilities, but the one that suggests itself most intuitively (when the masses and gauge couplings are turned on) is a cross product of the form

$$SU(48) > (G_V \times G_H) = G_F \quad (1.1)$$

where  $G_V$  ( $V$  for vertical) acts on the 16 (or 15) members of a family, and is the same for all families,

$$SU(16) > G_V, \quad (1.2)$$

While  $G_H$  ( $H$  for horizontal) acts on the 3 families. In the limit of zero  $\lambda$ ,  $G_F$  might satisfy  $U(3) > G_H$  or  $U(3) \times U(3) > G_H$ , etc, depending on the number of irreducible representations in which  $G_V$  classifies the 16 fermions. [Examples of such structures occur also in grand unified theories; e.g. for  $SO(10)$  grand unification  $G_V = SO(10)$ ,  $G_H = U(3)$ ; for  $SU(5)$  grand unification  $G_V = SU(5)$ ,  $G_H = U(3)_s \times U(3)_{10}$ ; for Pati-Salam unification  $G_V = SU(4) \times SU(2)_L \times SU(2)_R$ ,  $G_H = U(3) \times U(3)_R$  etc]. The main thing to notice is not the particular group, but the vertical x horizontal structure that one might expect if families are to be explained by compositeness, and that such an explanation is likely to lump together quarks and the leptons of 1 family within representations of  $G_V$ . This type of structure includes the possibilities that

- a) Family quantum numbers are carried by a set of family preons while the rest of the usual quantum numbers are carried by other preons.

- b) Family quantum numbers come from scalars or pairs of fermions that occur different number of times in different families.
- c) Family quantum numbers come from radial quantum numbers.

Thus, under the assumption  $G_F \sim G_V \times G_H$ , where  $G_V$  lumps quarks and leptons in one family, and  $G_H$  distinguishes families, we may analyze the kinds of 4-fermi interactions that must occur with a coupling  $\lambda^2/2A_F^2$ , where  $\lambda$  is of order 1. Here we find that there is always a term that mediates  $K \rightarrow \pi \mu e$  and/or  $K_L \mu e$ , namely

$$\frac{\lambda^2}{2A_F^2} [s_o \frac{(1+Y_s)}{2} d_o] [e_o \frac{(1+Y_s)}{2} p_o] + G_F \text{ symmetric terms} \quad (1.3)$$

where the  $o$ -index implies that these are the states before mass generation or Cabibbo mixing is taken into account. Assuming that these mixing angles are not large we see that the symmetry  $G_F = G_V \times G_H$  can never eliminate this term and thus we must require

$$A_F \geq (20-30) \text{ TeV}. \quad (1.4)$$

[Note that the decays occur for zero Cabibbo angles.] Models satisfying the reasonable assumptions above are therefore just beyond the reach of the SSC ( $E(\text{max}) = 10 \text{ TeV}$  in parton + parton center of mass with any appreciable luminosity).

Any model that manages to avoid the conditions of the theorem above is likely to do it in one of the following ways: either

- (i) Quarks and leptons are not linked within a family.
- or (ii) There is a set of one or more preonic  $U(1)$ 's that assign different quantum numbers to quarks than leptons and simultaneously distinguish families.
- or (iii) The mixing angles are large so that the mass eigenstate  $\tau, \mu, s, d$  correspond to  $e_o = \tau$ ,  $\mu_o = \mu$ ,  $s_o = s$ ,  $d_o = d$ . Instead of  $\tau, e_o$  may correspond to an even heavier lepton.

To these one could add less attractive possibilities that destroy the repetitive family structure, but we will not consider them here, since understanding family repetitions is one of the goals of compositeness.

In the first case it is evident we must give up a simultaneous explanation of quarks and leptons belonging to the same family. In such models it may turn out that leptons could artificially be added to the models by throwing in preonic degrees of freedom that are not required by the precolor dynamics. That is the model could be constructed for only the quarks<sup>7</sup>. We recall that the  $U(1)_V$  gauge anomaly in the standard model is the only evidence of a link between quarks and leptons of the same family. This gauge coupling has nothing to do with the precolor dynamics that yield composite quarks and leptons. A model which does not provide a dynamical link between quarks and leptons (in the absence of negligible couplings) may be possible, but we have to ask how palatable it is, since it breaks one of our intuitive expectations.

In the second case I suggest that it is attractive to associate the desired global  $U(1)$ 's with

the hypercharge  $Y$  of the standard model, since this is the only apparent link between quarks and leptons in each family. For example, consider 3 conserved preonic  $U(1)$ 's that assign separately the hypercharges in each family. [The gauge  $U(1)$  is the "diagonal"  $U(1)$ ]. These  $U(1)$ 's or an appropriate discrete subgroup embedded in them are sufficient to eliminate the dangerous terms of type (1.3). While this sounds attractive a model of this type has not yet been constructed.

The third case<sup>8</sup> of large mixing angles is also counter intuitive. However, here there may be room for much further investigation since an attractive mass generating mechanism does not yet exist. Note that even though mixing angles may completely be rotated away in the lepton sector in  $L$  (standard) (certainly so, if  $\nu_R$  do not exist), this is not necessarily the case in  $L(4\text{-fermi})$ . Since  $L(4\text{-fermi})$  is not quadratic in the fermions. Thus, in this mechanism the burden of suppressing  $K_L$ ,  $K$  rare decays rests with the mass generating mechanism without compromising the suspected linkage between quarks and leptons. The classification scheme for mass eigenstates is then expected to look as follows

$$\begin{aligned} \text{1st family } & \begin{pmatrix} \bar{u} \\ d \end{pmatrix}_L, u_R, d_R, \begin{pmatrix} \nu \\ \tau \end{pmatrix}_L, \tau_R, \nu_{\tau R} \\ \text{2nd family } & \begin{pmatrix} \bar{c} \\ s \end{pmatrix}_L, c_R, s_R, \begin{pmatrix} \nu \\ \mu \end{pmatrix}_L, \mu_R, \nu_{\mu R} \\ \text{3rd family } & \begin{pmatrix} \bar{t} \\ b \end{pmatrix}_L, t_R, b_R, \begin{pmatrix} \nu \\ e \end{pmatrix}_L, e_R, \nu_{eR} \end{aligned} \quad (1.5)$$

where  $\bar{u}$ ,  $\bar{c}$ ,  $\bar{t}$  are the  $(u, c, t)$  mass eigenstates rotated by the Cabibbo-Kobayashi-Maskawa mixing angle. With such a mass scheme, e.g. some of the models discussed in ref. 2,6 would completely avoid all the bounds discussed above.

Furthermore, by mixing the  $(u, c, t)$  quarks rather than the  $(d, s, b)$  quarks,  $A_s=1$  neutral current 4-fermi interactions do not occur. the family changing interactions that are generated by this mixing scheme are not restricted by known phenomenology. In  $L(\text{standard})$  it does not matter whether the ups or the downs mix, however, in  $L(4\text{-fermi})$  it makes an important phenomenological difference. Of course, the mass generating mechanism holds the secret for why the ups rather than the downs (or both?) should mix.

An example of trouble free 4-fermi interactions that illustrate the points above is explicitly exhibited in section 3.

## 2. COSMOLOGICAL UPPER BOUND ON $\Lambda_p$

In the previous section we discussed bounds coming from low energy physics. However, cosmological consideration can help probe the heavy sector  $M \sim \Lambda_p$  of a preon model if there are long lived states. This idea was first implemented in ref. 6, as outlined below.

A preon model often has some (naively) conserved  $U(1)$  quantum numbers. The low mass quarks and leptons can be taken neutral under some  $U(1)$  but some heavy states are charged. Then, in the same way that the proton is stable, such states are also (naively) stable.

Note that I emphasized naively conserved  $U(1)$ . This is because after stronger precolor instanton effects this  $U(1)$  may be broken (it is broken in ref. 6). However, one must still analyze the effective instanton interaction and estimate the rate at which the heavy state is allowed to decay. Then, an

interesting huge suppression may be found if the only allowed decays are to a large number of particles, despite a strong effective coupling constant. For example, the lifetime of a heavy scalar particle,  $M \sim \Lambda_p$ , that decays to  $N$  massless particles in the final state must be larger than

$$\tau \geq \frac{1}{(G^2 \Lambda_p)} \frac{(16\pi^2)^{N-1}}{\pi} \frac{(3N-4)!}{(4N-4)!} (2N-1)! (2N-2)! \quad (2.1)$$

Here  $G$  is a dimensionless effective coupling that measures the strength of the (instanton) interaction. A realistic model may require  $N$  of order 16, corresponding to the 16 members of a family, as in the example considered in ref. 6. Then

$$\tau \geq \frac{(100 \text{ TeV})}{G^2 \Lambda_p} (4 \times 10^{34}) \text{ years.} \quad (2.2)$$

Thus, even for a large value of  $\Lambda_p$ , the lifetime of such a particle is larger than the lifetime of the universe. This illustrates that  $U(1)$ 's that are broken by instanton effects should not be dismissed, as they may still lead to almost stable particles.

In the event that a preon model has long lived particles (even for lifetimes than several minutes), cosmological considerations can put limits on its  $\Lambda_p$ . In ref. 6, mainly the case of  $\tau \geq \tau(\text{universe})$  was discussed. It is estimated that the abundance of such stable particles in today's universe is

$$\frac{(N)}{N_Y \text{ today}} \sim \left( \frac{\Lambda_p}{M_{\text{planck}}} \right) \ln \left( \frac{M_{\text{planck}}}{\Lambda_p} \right) \quad (2.3)$$

For these not to dominate today's matter (baryons) dominated universe, we must require

$$\Lambda_p \leq 250 \text{ TeV.} \quad (2.4)$$

It may be possible to improve this bound by taking into account clustering of such particles in the form of galaxies. In any event, the fact that there is an upper bound in certain potentially realistic models and that the bound is fairly low is rather interesting from the point of view of the SSC.

## 3. A MODEL WITH EXOTICS

A preon model can be tested at low energies if it has exotic bound states that are  $G_F$ -partners of the (massless) quarks and leptons. The mass of such states is likely to be in the range

$$m_{\text{top}} < m < \Lambda_p, \quad (3.1)$$

thus requiring energies lower than  $\Lambda_p$  for discovering them. The recent jet activity around  $m \sim 150$  seen at the UA1 and UA2 detectors at CERN may be attributed to exotics, as discussed in the Compositeness Subgroup at the SSC Workshop<sup>9</sup>. The model presented here is an example which has a minimal number of exotics [1 color nonet (8+1)], and can provide signals of the type seen at CERN.

The precolor group is taken as  $G_p = SU(4) \times SU(4)$  and the preons are placed in the three representations  $R_1 = (4, 4)$ ,  $R_2 = (4, 1)$ ,  $R_3 = (1, 4)$ . The numbers and helicities of the preons are

$$1_L R_1 + 4_L R_2 + (10_L + 6_R) R_3, \quad (3.2)$$

Thus, the preflavor symmetry  $G_F$  which classifies the preons and composites is (after instanton effects)

$$G_F = SU(4) \times SU(10) \times SU(6) \times [U(1)]^2 \times Z^2 \quad (3.4)$$

The massless composites which satisfy anomaly, decoupling and certain other conditions for the entire conserved  $G_F$  are:

$$(4, 10, 1)_L^{(1,0)} (4, 1, 6)_R^{(0,1)} \quad (3.4)$$

This solution was used before in refs. (2,6) (without exotics) with a different interpretation of the "flavor" quantum numbers than the one suggested below.

We embed  $SU(3) \times SU(2) \times U(1)$  in  $G_F$  so that the preons are classified as follows:

$$\begin{aligned} R_2: 4_L \rightarrow (3, 1)_{1/6} + (1, 1)_{-1/2} \\ 10_L \rightarrow (1, 2)_0 + (1, 2)_0 + (1, 2)_0 + (\bar{3}, 1)_{-1/6} + (1, 1)_{1/2} \\ R_3: 6_R \rightarrow (1, 1)_{1/2} + (1, 1)_{-1/2} + (1, 1)_{1/2} + (1, 1)_{-1/2} + (1, 1)_{1/2} + (1, 1)_{-1/2} \end{aligned} \quad (3.5)$$

The subscripts are the  $U(1)$  quantum numbers. Note that this embedding is anomaly free for gauged  $SU(3) \times SU(2) \times U(1)$ , as it should be. QCD is embedded in  $SU(4)$  a la Pati-Salam. Therefore, the composites are classified as  $(4 \rightarrow 3 + 1)$

$$\begin{aligned} (4, 10, 1)_L &\rightarrow \begin{cases} 3: 3 \times (3, 2)_L^{1/6} + (3, 1)_L^{2/3} + (1, 1)_L^0 + (8, 1)_L^0 \\ 1: 3 \times (1, 2)_L^{-1/2} + (\bar{3}, 1)_L^{-2/3} + (1, 1)_L^0 \end{cases} \\ (4, 1, 6)_R &\rightarrow \begin{cases} 3: 3 \times (3, 1)_R^{2/3} + 3 \times (3, 1)_R^{-1/3} \\ 1: 3 \times (1, 1)_R^0 + 3 \times (1, 1)_R^{-1} \end{cases} \end{aligned} \quad (3.6)$$

This corresponds to 3 usual families of quarks and leptons plus a fourth up quark, plus a color nonet  $(3 \times 3^*, 1) = (1, 1)_L^0 + (8, 1)_L^0$  and a singlet  $(1, 1)_L^0$ . The quarks and leptons may be identified as in (1.5) so that  $\Lambda_c$  is not restricted by the rare processes discussed in section 1.

The point of this model is the presence of the nonet so that the singlet and octet have the same global quantum numbers, corresponding to a conserved  $U(1)$  embedded in  $G_F$ . Suppose the octet is heavy. If produced in pp reactions at CERN it can decay to a pair of quark + antiquark plus the neutral singlet that carries the same global quantum number as the octet. Thus in the final state one would see a pair of highly energetic jets plus missing energy. Since one of the quarks may sometimes be slow, the event (after the cuts) can also look as 1 energetic jet plus missing energy. The cross section for production + decay is quite large and can explain the rates seen at CERN, as discussed in the compositeness group in this workshop.<sup>9</sup> Note that the octet of this model has some properties similar to the gluino in supersymmetric theories, if the gluino is taken at around the same mass, and may be confused with it.

More model independent properties of exotics, are discussed in ref. 9.

I wish to propose another important role for exotics in a composite model. Marciano<sup>10</sup> suggested that high color states (6, 8, 10 etc.) may condense at the electroweak scale  $F_\pi \sim 250$  GeV, thus providing a mechanism of mass generation analogous to technicolor but only with QCD forces. In the context of composite models this idea is quite attractive because

(i) Exotics occur naturally

(ii) The 4-fermi interactions provide masses for quarks and leptons after condensation.

In the models of elementary quarks and leptons discussed in ref. 10, it was difficult or unattractive to implement a substitute for (ii).

To use this mechanism one must address questions<sup>12</sup> about the asymptotic freedom of QCD because, if QCD loses its asymptotically free behaviour due to many exotics, condensation would take place at the highest values of  $\alpha_{QCD}$ , thus at the highest scales. This is not desirable. For this I emphasize that in a composite model we must separately consider the calculation of  $\beta_{QCD}$  in the regimes below  $\Lambda_c$  and above  $\Lambda_c$ . Below  $\Lambda_c$  there are few and non-exotic preons. In terms of preons  $\beta_{QCD}$  must and can easily be negative for asymptotic freedom to be correct. Below  $\Lambda_c$  the behaviour of  $\alpha_{QCD}$  or  $\beta_{QCD}$  may be smooth or complicated depending on the number of exotics and their thresholds. In the range  $\Lambda_{QCD} < \mu < \Lambda_c$  condensation will occur if  $\alpha_{QCD}(\mu)$  attains the critical value at  $\mu = F_\pi = 250$  GeV

$$\alpha_{critical} = \alpha_{QCD}(F_\pi) \quad (3.7)$$

[ $\alpha_{critical}$  may approximately be estimated<sup>10,11</sup> via the quadratic casimir for the exotic representation  $R$ ,  $C_2(R)\alpha(F_\pi)=1$ ]

For  $\mu > F_\pi$ ,  $\alpha(\mu)$  must never exceed  $\alpha_{critical}$ , otherwise the scheme will not have any meaning. Two possible situations are shown in Figs. 1 and 2

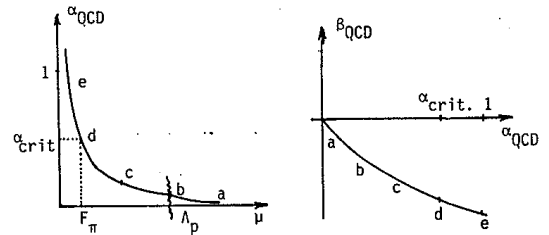


Fig. 1. Few exotics.  $\beta < 0$  for all scales.

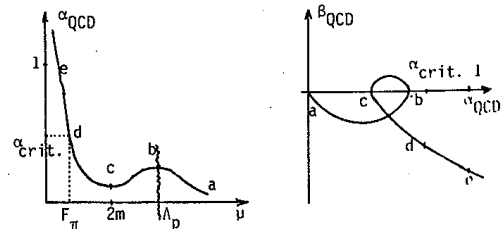


Fig. 2. Many exotics.  $\beta > 0$  above  $2m$  threshold;  $\beta < 0$  above  $\Lambda_c$ .

In Fig. 1, even below  $\Lambda_D$ , there are few exotics so that the  $\beta$  function (slope of  $(\alpha(\mu))$  always remains negative. In Fig. 2, there are too many exotics below  $\Lambda_D$ . The threshold for producing the exceeding exotics is  $\mu=2m$ , above which  $\beta_{QCD}$  is positive. However beyond  $\Lambda_{QCD}$  is again negative since the computation is done in terms of preons. Note the interesting multivalued plot of  $\beta$  versus  $\alpha$  for this case which, as explained, can happen quite naturally in a composite model. Each branch of this curve is computed perturbatively since  $\beta_{QCD}(\mu)$  is small. The non-perturbative phenomena occurring via the underlying precolor forces is what gives rise to such a non-perturbative looking curve.

For these mechanisms to be useful for electroweak symmetry breaking there should be some exotics carrying electroweak quantum numbers, such that  $\Delta I^W=1/2$ . These could be of the form  $(r, 2)_L + (r, 1)_R$  where  $r$  is a complex representation of  $SU(3)$ , such as  $r=6, 10$ , etc., and 2 is a doublet, 1 is singlet of  $SU(2)_L$ . The numbers of doublets and singlets could be such that the symmetry breaking preserves a custodial  $SU(2)$  (approximately). We cannot allow  $r$  = real (e.g.  $(8, 2)$ ) since this would lead to  $\Delta I^W=1$  via  $(r, 2)_L \times (r, 2)_L \rightarrow (1, 3)$ . Any real exotic representation should not simultaneously be a doublet of  $SU(2)_W$  (e.g.  $(8, 1)$  is o.k.). As Marciano estimates, 2 sextets together with the usual 3 families just about saturate asymptotic freedom for QCD. Thus, although there is the possibility of a composite model described by Fig. 1, most models with exotics are likely to be described by Fig. 2, if they play any role in electroweak symmetry breaking.

Models with exotics now being investigated will be described in future publications.

#### ACKNOWLEDGEMENT

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- (5) The reader should be aware that the different definitions of compositeness scales imply bounds that may seem different by a factor of 5, but can be translated to be in agreement with each other. In QCD the mass of the rho satisfies  $m_\rho \approx (3-5) \Lambda_{QCD}$  where  $\Lambda_{QCD}$  is thought to be in the range 150-250 MeV.  $\Lambda_D$  is defined in analogy to  $\Lambda_{QCD}$ . Other authors (e.g. ref 3,4) have used the mass of the expected composite vector meson  $\Lambda^*$  as a convenient scale. By analogy to QCD we might expect  $\Lambda^* \approx (3-5) \Lambda_D$ . Thus the strength of the 4-fermi interaction parametrized in ref 2 as  $\lambda^2/2\Lambda_D^2$ , with  $\lambda$  of order 1, is consistent

with  $4\pi/2\Lambda^*{}^2$  used in ref. 3,4.

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- (7) A model which appears to fall in this category was described to me by O. W. Greenberg and S. Nussinov after this workshop: The composites contain a fermion and a boson  $(\psi\phi)$ ;  $\psi_{L,R}$  carry  $SU(2)_L \times SU(2)_R$ , while  $\phi_{a1}, \phi_{i1}$  carry  $a=$ color,  $i=$ lepton,  $i=$ quark family,  $I=$ lepton family (different than quark family).
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HIGH- $p_T$  PHOTON PRODUCTION AND COMPOSITENESS AT THE SSC

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Summary

The yield of direct photons for  $p_T \geq 1$  TeV/c is large enough to probe predictions of conventional QCD as well as to examine consequences of the compositeness of quarks at a scale of  $\sim 5$  TeV.

Direct photon production in high- $p_T$  processes can serve as a useful probe of the underlying parton-parton interactions.<sup>1</sup> In this report we shall present predictions for high- $p_T$  photon production based on conventional QCD dynamics and contrast them with what may be expected if the energy scale for composite quarks is on the order of 10 TeV.

Direct photons are produced in QCD via the two subprocesses  $q\bar{q} \rightarrow \gamma g$  (annihilation) and  $qg \rightarrow \gamma q$  (Compton). In addition, there is a bremsstrahlung contribution wherein the outgoing partons fragment into a hard photon and accompanying hadrons. In Fig. 1 predictions for jet,  $\pi^0$ , and  $\gamma$  production are shown at  $y = 0$ . The corresponding ratios for  $\gamma/\text{jet}$  and  $\gamma/\pi^0$  are given in Fig. 2. At low  $p_T$  values, the brem/direct  $\gamma$  ratio is sizeable (4.5 at  $p_T = 100$  GeV/c). However, the ratio falls rapidly, and by  $p_T = 1.5$  TeV/c it is only 30%. The rapidity distribution for direct photons is rather flat over a wide range in  $y$ . This is shown in Fig. 3 for two values of  $p_T$ . The contributions from the Compton graph are shown separately in Fig. 3.

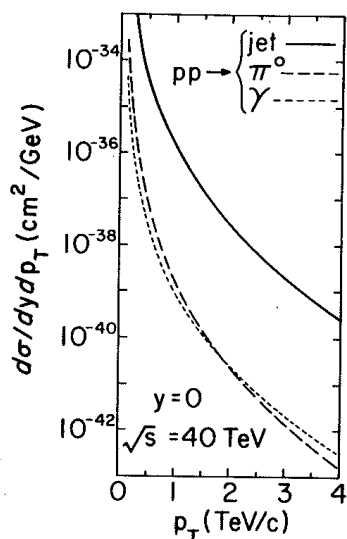


Figure 1. Predictions for  $d\sigma/dydp_T$  at  $y=0$  for jet (solid curve),  $\pi^0$  (dashed curve) and  $\gamma$  production.

These predictions suggest that even though the  $\gamma/\text{jet}$  ratio is on the order of  $10^{-3}$  for  $p_T > 1$  TeV/c, there is, nevertheless, an adequate yield of photons available for a quantitative experimental investigation of the signal.

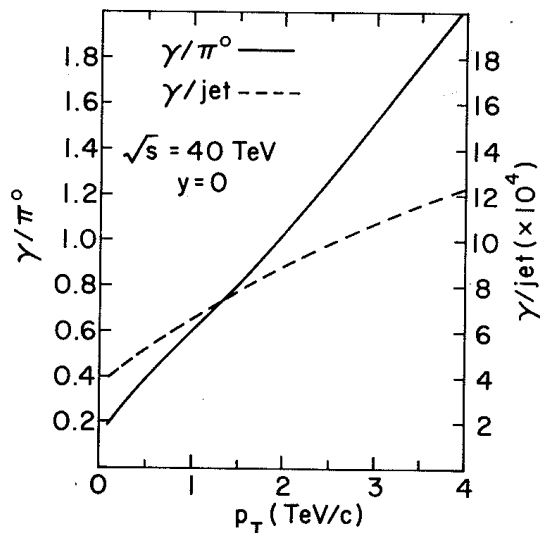


Figure 2. Predictions for the  $\gamma/\text{jet}$  and  $\gamma/\pi^0$  ratios at  $y=0$ .

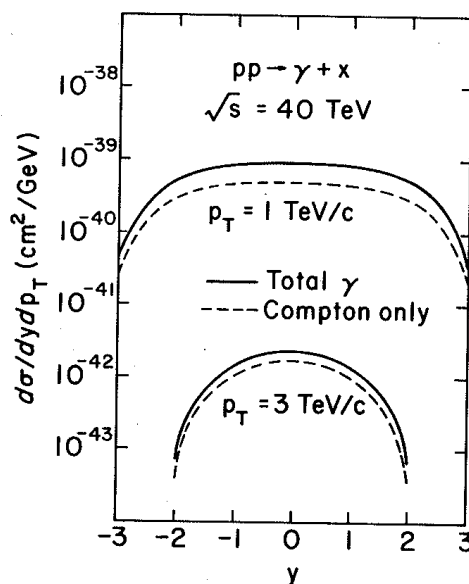


Figure 3. Predictions for  $d\sigma/dydp_T$  for  $\gamma$  production at  $p_T = 1$  TeV/c and 3 TeV/c.



Background to the direct-photon signal at large  $p_T$  will be primarily from  $\pi^0$ 's and  $\eta$ 's (or multi- $\pi^0$ , low-mass, objects) whose decay photons cannot be resolved in a calorimeter. This background should not be important at such high  $p_T$ , however, because  $\pi^0$ 's and  $\eta$ 's are not produced directly, but are rather fragments of quarks or gluons and must consequently be accompanied by the other hadronic remnants of the (massive) jet.

A relatively straightforward trigger for accumulating a clean sample of direct-photon data would require  $\geq 1.0$  TeV of energy deposition in a localized transverse area of about  $4 \text{ cm} \times 4 \text{ cm}$  of an electromagnetic-calorimeter tower, with no substantial energy ( $< 0.05$  TeV) deposition in the hadronic part of the tower that shadows this electromagnetic front. With an average number of  $\sim 25$  hadrons in the core of a jet,<sup>2</sup> these requirements would essentially eliminate any  $\pi^0$  or  $\eta$  background to the direct-photon signal.

Table I shows the expected yield of direct photons, just from the Compton graph, per year of running time at a luminosity of  $10^{33} \text{ cm}^{-2} \text{ sec}^{-1}$ , for an electromagnetic calorimeter of the type described by Feldman.<sup>3</sup> It is clear from the table that QCD event rates will be sizeable, even for  $p_T \geq 1 \text{ TeV/c}$ .

Table I. Expected Yield of Direct Photons From the Compton Diagram

$p_T$ (TeV/c)	$\frac{d\sigma}{dp_T dy} \Big _{y=0}$ ( $\text{cm}^2/\text{GeV}$ )	Yield (Events/0.5 TeV/year)
0.5	$0.91 \times 10^{-38}$	$8.7 \times 10^5$
1.0	$0.41 \times 10^{-39}$	$3.2 \times 10^4$
1.5	$0.58 \times 10^{-40}$	$3.3 \times 10^3$
2.0	$0.13 \times 10^{-40}$	$6.8 \times 10^2$
2.5	$0.39 \times 10^{-41}$	$1.7 \times 10^2$
3.0	$0.13 \times 10^{-41}$	54
3.5	$0.51 \times 10^{-42}$	17
4.0	$0.23 \times 10^{-42}$	8

Now, to address the question of compositeness, we must consider two regimes of interactions. One, is when the collision  $\hat{s}$  value is below the characteristic compositeness scale  $\Lambda^2$  and, second, when  $\hat{s}$  is above this parameter. Below  $\Lambda^2$ , in addition to the standard QCD contributions, there will be contact interactions that give rise to direct photon production. There are, unfortunately, no operators of dimension six (with amplitude of order  $\hat{s}/\Lambda^2$ ) that can lead to production of photons in the annihilation or in the Compton QCD processes. (We thank E. Eichten and S. Parke for bringing this result, due to R. K. Ellis, to our attention; see R. K. Ellis, Nucl. Phys. B106, 239 (1976).) The first non-vanishing operators are of dimension eight. There is no reason to expect that these operators are particularly enhanced and, consequently, their contribution will be suppressed relative to the QCD amplitude by  $\sim (\hat{s}/\Lambda^2)^2$ . If we take the constituent and QCD amplitudes to be relatively real, then we can write for the total  $\gamma$  yield the following approximate coherent sum:

$$\sigma_{\text{Compton}} \left[ 1 + \left( \frac{\hat{s}}{\Lambda^2} \right)^2 \right]$$

In Fig. 4, predictions based on the Compton process alone (which dominates at high  $p_T$ ) are shown for  $\Lambda = \infty, 8, 5$ , and  $4 \text{ TeV}$ . These predictions may be compared directly to the corresponding jet predictions in reference 4.

For  $\hat{s} > \Lambda^2$ , a spectrum of new quark excitations would be expected in the direct  $gq \rightarrow q\gamma$  channel, with  $q^* \rightarrow g\gamma$  likely to proceed at the  $\geq 10^{-3}$  level. This

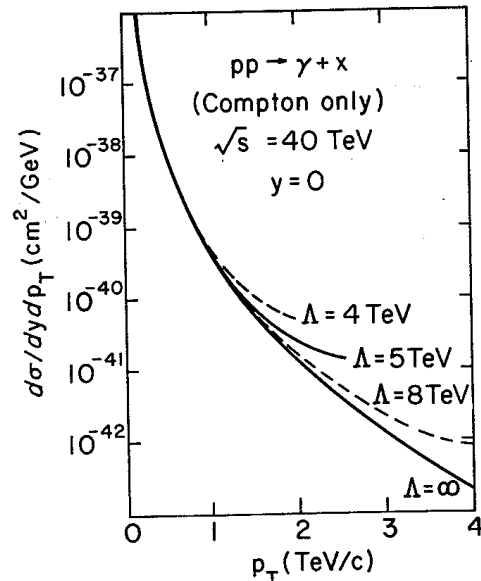


Figure 4. Predictions for  $d\sigma/dydp_T$  based on the Compton process, modified to include effects of compositeness. Results are shown for  $\Lambda = \infty, 8, 5$ , and  $4 \text{ TeV}$ .

new source of photons would produce peaks in the  $\gamma$ -jet mass distribution, with widths that would depend on the nature of the excited quark states. If we take the normal low-lying particle states as a guide, where widths are typically of the order of  $\sim 1/10$  the mass values, then we might anticipate substantial enhancement in the  $\gamma$  yield at  $p_T \sim 1/2 \Lambda$ , and possible oscillations with widths of  $\sim 1/10 \Lambda$ .

To conclude, it appears that direct-photon events can provide clean signals that can be used to study QCD at large  $p_T$  and probe compositeness to scales of order  $5 \text{ TeV}$ .

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LOW ENERGY SIGNALS OF COMPOSITE MODELS\*

Compositeness Study Group at the SSC Theoretical Workshop

R. Barbieri, I. Bars, M. Bowick, S. Dawson, K. Ellis, H. Haber, B. Holdom, J. Rosner, M. Suzuki.

Some signals of compositeness that represent deviations from the standard model at low energies are discussed. Emphasis is given to exotic composites, strong P,C violation beyond the weak interactions and small deviations in relations among the parameters of the standard model. Such effects may be detected at energies obtainable at CERN, LEP and the SSC.

EXOTIC COMPOSITES

If quarks and leptons are composites of preons with a scale  $\Lambda_p$ , their low mass ( $m \ll \Lambda_p$ ) can be understood only if there is a preonic chiral flavor symmetry group  $G_F$  that is not spontaneously broken in the vacuum.  $G_F$  must include  $SU(3)_c \times SU(2)_W \times U(1)_Y \times$  Baryon Number  $\times$  Lepton number  $\times$  family quantum numbers. If all forces, except the strong precolor forces, are neglected at the scale  $\Lambda_p$ ,  $G_F$  may appear to be a much larger symmetry. Since the formation of the bound states at  $\Lambda_p$  has nothing to do with the other smaller forces, (e.g. QCD), it is a good approximation to use the enlarged (globally conserved)  $G_F$  to classify all massless or massive composites in irreducible representations of  $G_F$ .

The massless composites, classified as  $\{R\}$  under  $G_F$ , must satisfy certain consistency conditions<sup>1</sup> if the symmetry  $G_F$  is to remain unbroken. General unique solutions have been given to a set of very restrictive conditions<sup>2</sup>. Thus, it is now known that there exists a classification of possible precolor groups and precolor representations (preons) that yield a predetermined set of massless composite states  $\{R\}$ . Potentially realistic examples can be found among these models.

The next stage is to analyze the  $SU(3) \times SU(2) \times U(1)$  content of these representations to determine the quark and lepton structure. There may be more than one way of embedding  $SU(3) \times SU(2) \times U(1)$  in  $G_F$ ; each embedding may give a different structure. One may find along with the massless quarks and leptons that there are massless exotic composites in the sense that they carry high color or high weak-isospin or high hypercharge (or electric charge):

$$\begin{aligned} \{R\} \rightarrow \text{leptons} &= \{(1, 1)_Y\} \\ &+ \text{quarks} = \{(3, 1)_Y\} \\ &+ \text{High color} + \{(6 \text{ or } 8 \text{ or } 10 \text{ etc.}, 1)_Y\} \end{aligned}$$

where the isospin  $I$  and hypercharge  $Y$  may take non-exotic or exotic values. The emergence of exotics is not necessary in every model (see e.g. ref. 2) but they may occur quite naturally in many models.

When the symmetry is broken from  $G_F$  to  $SU(3) \times SU(2) \times U(1) \times$  Baryon no.  $\times$  Lepton no., the exotics must become massive while the ordinary families are still massless (exact  $SU(2)$ ). Since by definition of  $G_F$ , this breaking is assumed to occur at a scale  $\mu$  considerably smaller than  $\Lambda_p$ ,  $\mu \ll \Lambda_p$ , the exotics are much lighter than the heavy composites. The study of exotics is therefore interesting since they may provide some clues<sup>2</sup> of compositeness at energies much smaller than  $\Lambda_p$ . Furthermore, it is conceivable that high color exotics may play a role in electroweak symmetry breaking<sup>3</sup> at 250 GeV and generate masses for the quarks and leptons in a composite model<sup>4</sup>. The

abnormally energetic events seen at UA1 and UA2 at CERN may be associated with exotics.

These remarks provide some motivation for studying exotics at this workshop. We report here two possible occurrences of exotics 1) Exotics produced freely, 2) Exotics within non-exotic bound states. We concentrate on high color exotics since their production cross section is large in pp reactions already at CERN energies.

In the reaction

$$pp \text{ or } p\bar{p} \rightarrow Q\bar{Q} + \text{anything}$$

The pair of high color exotics ( $Q\bar{Q}$ ) may be produced freely or in a bound state, depending on the strength of the QCD color force that acts on them. The bound state may be in the form of  $\bar{Q}Q$ -onium (like charmonium) or in the form of a pseudo-goldstone ( $\eta'$ -like object) if high color plays a role in electroweak symmetry breakdown at 250 GeV. The observation in the form of a bound state is possible only if the lifetime of the composite state is shorter than the lifetime of the individual exotic fermions.

The dominant parton subprocess in the production of high color exotics is gluon fusion  $g + g \rightarrow Q\bar{Q}$ . The production cross section is enhanced by color factors relative to the production of heavy triplet quarks, bound or free. The production of a bound state  $X=Q\bar{Q}$  is given by

$$\sigma(pp \rightarrow X + \text{any}) = \frac{\pi^2 \Gamma_X}{8M_X^3} \left( \frac{dL}{d\tau} \right) \bigg|_{\tau=M_X/s} \left[ q_r^2 \frac{3}{d_r} \right]$$

where  $\Gamma_X$  is the decay rate of  $X \rightarrow gg$  if  $Q$  is a color triplet,  $\tau dL/d\tau$  is the parton effective luminosity factor, as given in ref. 5., and the last bracket is a color factor for the color representation  $r$ :  $d_r$  is the dimension of the representation and  $q_r$  is related to the quadratic casimir operator normalized to 1 for a triplet

$$\frac{d_r}{q_r} = \begin{array}{cccccc} & 3 & 6 & 8 & 10 & \dots \\ \hline & 1 & 5 & 6 & 15 & \dots \end{array}$$

For  $M_X=150$  GeV, we estimate  $\Gamma(X \rightarrow gg) \approx 1-10$  MeV for either  $\bar{Q}Q$ -onium type bound state or goldstone type bound state. At CERN energies,  $\sqrt{s}=540$  GeV, the luminosity factor gives a cross section

$$\sigma \sim (10^{-7} - 10^{-6}) \text{ nb}$$

which is too small to produce any appreciable number of events. Thus, surprisingly such bound states may hide quite well at CERN. However, at the SSC, for  $M_X \sim 1$  TeV,  $\Gamma_X$  is estimated to be  $\approx 300$  MeV, and at  $\sqrt{s} = 40$  TeV the much larger luminosity factor produces

$$\sigma \sim 10^{-2} \text{ nb}$$

The analysis of the signals may be done as described in ref. 6, for a similar bound state of two gluinos. Such a state may produce detectable signals at the SSC.

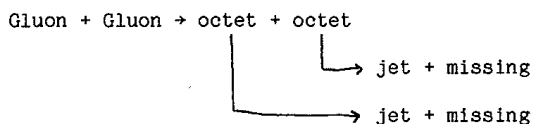
The free production and subsequent decay of certain exotics can produce a much larger number of events so that their detection is enhanced by many orders of magnitude. See, for example, estimates of gluino production and detection at CERN<sup>7</sup> or the SSC energies<sup>5</sup>. Composite exotics with certain properties that can produce energetic jet signals plus large missing energy with cross section of the size alleged to be detected at CERN can exist in composite models. A minimal example of a model containing a zero-charge color nonet  $L_8 + L_1$  is given in ref. (4). In the low energy theory one finds effective couplings of the form

$$L_{eff} = \bar{L}_8 i \not{D} L_8 + \bar{L}_1 i \not{D} L_1 + \frac{g}{\Lambda_p} \bar{L}_8 F_{\mu\nu} \sigma^{\mu\nu} L_1$$

where  $D L_8 = \partial L_8 - ig [A, L_8]$  couples the gluon to a pair of octets and  $g/\Lambda_p$  describes the magnetic coupling for the gluon + octet + singlet. Since the octet and singlet carry the same global quantum numbers (they come from a nonet) the magnetic coupling is not suppressed by factors of  $(\text{mass}/\Lambda_p)$ . Thus, the octet decays dominantly to the singlet plus a gluon with a decay rate

$$\Gamma_8 \approx \frac{1}{\pi} \alpha_{QCD} M_8^2 / \Lambda_p^2$$

This may be small, but since it is nearly 100% branching ratio, it is only the magnitude of the production rate that determines the number of events in the final state. The production cross section for the octet is large at the CERN (and higher) energies, as estimated<sup>7</sup> for production of 40 GeV gluinos in supersymmetric theories, and can produce many events with jets + missing energy of the type and numbers alleged to be seen at CERN. Thus



produces signals of the type

proton + (anti-) proton → jet + jet + missing + anything

with the characteristics of the CERN events at UA1 and UA2. If one of the octets has a slow forward momentum, the momentum cuts will make it appear as if there was only 1 energetic jet in the final state. Thus the mono-jet and two-jet events with approximately correct size cross sections may be explainable by composite exotics.

There may exist other exotics with interesting properties. For example, a sextet plus a triplet with the same global  $U(1)$  quantum numbers will have effective interactions of the type described above. The decay rate for sextet → triplet + gluon is similar in magnitude to the octet described above. [If the triplet does not share the same global quantum number as the sextet, then  $\Gamma_6$  is suppressed by a factor  $(m/\Lambda_p)^2$ ]. The production and decay of a pair of heavy sextets will now produce  $2 + 2 = 4$  energetic jets in the final state without any large missing energy. This kind of signal may help or destroy certain models.

An excited triplet quark, which also has unsuppressed magnetic couplings with a gluon and a quark, would differ from the properties of the sextet described above. For one thing, the mass of  $Q^*$  is likely to be of order  $\Lambda_p$ . But, if somehow its mass were low, it will be expected to have effective magnetic couplings  $Q^* \sigma^{\mu\nu} q F_{\mu\nu}$  with  $F =$  photon,  $W$ ,  $Z$  in addition to gluon. Thus, from the ratio of the coupling constants for

$$Q^* \rightarrow q + g : Q^* \rightarrow q + \gamma : Q^* \rightarrow q + W : Q^* \rightarrow q + Z,$$

taken proportional to the strengths of the gauge coupling constants, one may estimate the ratio of number of events for

$$\text{jet} + \text{jet} : \text{jet} + \gamma : \text{jet} + e\nu : \text{jet} + \nu\nu : \text{jet} + e\bar{e},$$

with a result

$$10 : 1 : 0.3 : 0.7 : 0.1$$

Unfortunately, this pattern does not appear to correspond to present observations. Furthermore, the absolute number of events would be too small if the magnetic coupling is of order  $1/\Lambda_p$ . (The sextet described above, if charged or if it has weak isospin, would also produce signals of the type discussed here.)

It appears that further study of exotic composites, with possible applications at CERN or the SSC, is warranted.

#### STRONG P,C VIOLATION

In the models with purely fermionic preons it appears impossible to preserve global flavor chiral symmetry if the gauge precolor interaction is vector-like<sup>2</sup>. By contrast, in left-right asymmetric chiral theories the necessary chiral preservation conditions can be satisfied<sup>8,2</sup>. Thus, we are biased to believe that a preon theory is likely to violate parity (P) and charge conjugation (C) (but perhaps not PC) by large amounts at the scale  $\Lambda_p$ , since the classification of composites and the dominant strong interactions (precolor) are expected to be left-right asymmetric. (Theories with scalar preons may avoid this conclusion). If we were doing experiments at energies near  $\Lambda_p$  this fact, if true, would be readily apparent. However, at low energies  $E \ll \Lambda_p$ , the effective Lagrangian contains symmetry violating effects in terms proportional to  $1/\Lambda_p$  (such as 4-fermi terms), which are not easily detectable until the energies are sufficiently high. As emphasized since the early days<sup>8,2</sup>, it is very interesting to test this distinguishing aspect of preon models by looking for P or C violating effects that increase with energy and eventually surpass in magnitude the parity violation of the weak interactions.

In this workshop we considered the possibility of polarized proton beams to help determine the chirality (and hence the P,C properties) of the contact 4 fermi interactions with strength  $1/\Lambda_p^2$ . The initial discussions revealed mainly the difficulties: At the SSC energies mainly the sea partons dominate<sup>5</sup>. Therefore we do not expect much effect from the initial polarization of the proton which is mostly shared by the valance quarks. Furthermore, in the final state we cannot distinguish a quark jet from an

anti-quark jet. This prevents distinguishing final helicities. In addition, since the expected asymmetries are small at  $E \ll \Lambda_p$ , the parton distributions must be better understood to clearly disentangle the effect.

Another possible test of P,C violation in contact terms involves polarized electron-electron or electron-positron scattering. The available energies and resulting effect are of course much smaller, but the signal would be cleaner. One could measure forward-backward asymmetries in  $ee+ee$  or  $ee+ee$  with initially polarized electrons. Some estimates have been done by Peskin<sup>9</sup>. A more interesting test would be a measurement of  $ee+\pi\pi$  with initially polarized beams and observation of the polarizations of stopped  $\pi$ ,  $\tau$ . A deviation from the helicity amplitudes and rates of the standard model may indicate the presence of contact terms with certain helicity properties. General 4-fermi helicity amplitudes and cross sections that can be applied to this problem are defined in ref. 10.

In addition to separate P,C violation it is interesting to consider (PC=T) violation in the contact terms, although there is no compelling theoretical reason to expect it. A possible effect involves the quantity

$$\left. \frac{d\sigma}{dq dy} \right|_{y=0} (p\bar{p}+e\bar{v}) - \left. \frac{d\sigma}{dq dy} \right|_{y=0} (p\bar{p}+e\tau\nu) \equiv A$$

A signal above the standard model background would result if the 4-fermi strength is  $\lambda^2/2\Lambda^2$ , with  $\lambda^2=4\pi$ ,  $\Lambda \sim 5$  TeV, and  $\sqrt{q^2}$  is larger than 500 GeV. For example, at  $\sqrt{q^2} = 1.5$  TeV the quantity A would be 5 times larger than the Drell-Yan background. The effect gets larger as  $\sqrt{q^2}$  increases.

By far the surest way to observe the possible strong P,C violation is to do experiments at large energies  $E \geq \Lambda_p$ . If  $\Lambda_p$  is not large relative to the SSC center of mass parton-parton energies (see ref. 4) the best way to distinguish viable models may be through asymmetries. Estimates of asymmetries have not yet been done for such energies, but a formalism that provides the methods and some cross section estimates at  $E \geq \Lambda_p$  has been developed.<sup>10</sup>

#### SMALL DEVIATIONS IN THE STANDARD MODEL

Most discussions on tests of compositeness at low energies concentrate on new phenomena due to the non-renormalizable pieces in the effective Lagrangian. However, because of the electroweak symmetry breaking, the effects of compositeness may trickle down to the dimension  $\leq 4$  operators in the standard model. These effects which boil down to shifts in the W, Z masses, the  $\rho$  parameter, or the Z couplings, may be measurably large in precision experiments as discussed in more detail refs. 11, 12.

As an example consider the Y-Z kinetic mixing of ref. 12. This arises from an  $SU(2) \times U(1)$  invariant term in the effective Lagrangian

$$-\frac{1}{2} \xi g' / \Lambda^2 B_{\mu\nu} \text{Tr} [M^\dagger [D_\mu D_\nu] M \tau_3]$$

where M is the  $2 \times 2$  matrix of  $[SU(2) \times U(1)]/U(1)$  Goldstone boson fields (effective Higgs),  $D_\mu M = \partial_\mu M - ig W_\mu (\tau/2) M + ig' M (\tau_3/2) B_\mu$ , and  $B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$  is the field for B. Note the presence of  $\tau_3$  that breaks the right handed isospin. This is assumed to arise from an underlying preon theory or extended

technicolor theory) with the ability to generate up-down mass differences. Electroweak spontaneous breakdown allows us to replace M by the vacuum expectation value v, thus generating B-Z or Y-Z mixing in the form

$$-\frac{1}{2} \xi' \cos \theta A_{\mu\nu} Z^{\mu\nu}$$

where  $A_{\mu\nu}$  and  $Z_{\mu\nu}$  are the photon and Z field strengths, and  $\tan \theta = g'/g$  is the Weinberg angle. The parameter  $\xi'$  may be estimated by relating it to 4-fermi interactions that violate the right-handed isospin. It's magnitude may be as large as  $\xi' \sim 0.01$ , unless it is suppressed by a factor  $(v/m_0)^3$ .  $m_0$  is the dynamically generated mass of a high-color or technicolor quark.

It can be shown that this mixing  $\xi'$  leads to a redefinition of the measured Weinberg angle  $\tilde{S}$

$$\tilde{S}^2 = \sin^2 \theta + \xi' \sin \theta \cos^2 \theta,$$

and to a modification of the relationship between the measured masses of W, Z and the Weinberg angle  $\tilde{S}$ , and electric charge:

$$m_W = \frac{1}{2} \left( \frac{ev}{\tilde{S}} \right) \left[ 1 + \frac{\xi'}{2\tilde{S}} (1 - \tilde{S}^2) + \dots \right]$$

$$m_Z = \frac{1}{2} \frac{ev}{\tilde{S}\sqrt{1-\tilde{S}^2}} \left[ 1 - \xi'/2\tilde{S} + \dots \right]$$

This causes a shift in  $m_W$  or in  $m_Z$  up to 1% if not suppressed by  $v/m_0$ . However, since the effective interaction above is only an example, a more general structure can lead to a larger shift in  $m_Z$ ,  $m_W$ , according to the more general formulas in ref. 12. It is hard to obtain a precision measurements of  $m_W$  with present techniques. However, measurements at the Z resonance could reveal shifts in  $m_Z$ , as well as modifications in the couplings of the Z, as in eq. 46 of ref. 12, thus signaling deviations from the standard model due to the presence of a higher scale.

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### Summary

We examine a variety of issues connected with searching for compositeness at the SSC. These include effects of resolution, alternative methods of looking for deviations from QCD predictions, advantages of polarized beams, and effects of compositeness on photon detection. We also consider how physics may look if the compositeness scale is as low as a few TeV.

### Introduction

The idea that quarks and leptons might be composite has a strong appeal. (For reviews see Peskin<sup>1</sup> and Bars<sup>2</sup>). Compositeness could provide an explanation for the repetitive structure of the generations and the origin of the fermion mass matrix, two of the outstanding puzzles of particle physics. Moreover, it is quite possible that the scale of compositeness,  $\Lambda$ , is within reach of the SSC. Current experiments set limits "only" of order a TeV on  $\Lambda$ <sup>3,4</sup> while many theoretical ideas suggest that  $\Lambda$  might be no more than a few orders of magnitude larger than the weak scale.

In theories without fundamental scalars (technicolor), in particular, quark and lepton masses must arise from physics in the TeV range, so this is a natural compositeness scale. Of course, quarks and leptons might not be composite, or the scale of their binding could be much greater than a TeV. If there are fundamental scalars, for example (as in supersymmetry), there is no reason that the quarks and leptons should not appear as fundamental down to the Planck mass. But all of us feel that compositeness just might be accessible to the SSC, and that it is something for which both theorists and experimenters must be alert.

Much work has already been done concerning searching for compositeness at the SSC, especially by Eichten, Hinchliffe, Lane, and Quigg<sup>5</sup> (EHLQ). In this section, we consider a number of more detailed questions.

On the theoretical side, there are a limited number of ideas and models from which we can receive some guidance. Most of us believe that any underlying preon theory will be an asymptotically free gauge theory, similar in some respects to QCD. The constituents of this theory, the preons, will be chiral fermions (and possibly fundamental scalars); this theory almost certainly will not preserve parity, to any approximation. At low energies, corresponding to wavelengths much larger than the scale of preon binding,  $\Lambda$ , the only modification to the standard model Lagrangian will be the appearance of non-renormalizable interactions such as four-fermi terms, form factors, and the like.<sup>1-4</sup> As the energy grows, quarks and leptons should reveal their true nature as strongly interacting particles--quark-quark (and lepton-lepton) scattering should resemble proton-proton scattering, with a cross section which is geometrical, and exhibits a great deal of structure. At scales much above  $\Lambda$  (if we may be permitted to dream, for a moment), we should resolve the fundamental preons, and physics should again scale. This QCD analogy has been pushed quite hard in past work, and we have pushed it a bit harder at this workshop.

Beyond this, we can get some guidance from experimental limits on rare processes and from existing models. In particular, Bars<sup>6</sup> has provided a catalog of some of the models which pass existing theoretical and experimental tests. (Unfortunately, one cannot say with certainty what the light spectrum of these theories is, nor does one have a theory for quark and lepton masses, but these models at least have the potential to be realistic). He has also listed some of the constraints which follow from limits on rare processes. In particular, some of the possible effective 4-fermi terms must have couplings smaller than  $(40 \text{ TeV})^{-2}$ , almost certainly a difficult constraint to satisfy

in model building, as experience in technicolor has shown.

Beginning with the pioneering work of Abolins et al., at the 1982 Snowmass Workshop,<sup>3</sup> there has been a great deal of effort to determine how one might search for compositeness at energies below  $\Lambda$ . In particular, Abolins et al. noted that the largest effects, in quark-quark (and lepton-lepton) scattering were likely to come from four-fermi operators, rather than from form factors, and they studied these operators in a variety of processes. Eichten, Hinchliffe, Lane and Quigg (EHLQ)<sup>5</sup> have extended these analyses to SSC energies. Focusing on one particular operator,

$$L_{qq} = n_0 \frac{g^2}{2\Lambda^2} \bar{q}_L \gamma^\mu q_L \bar{q}_L \gamma_\mu q_L \quad (1)$$

where  $g^2 = 4\pi$  (by analogy to the  $\phi$  coupling),  $n_0 = \pm 1$ , they studied deviations from QCD predictions for high  $p_\perp$  single jet production, for fixed beam energy. They argued that the SSC could set a limit on  $\Lambda$  of 20 TeV in this way (Assuming  $\sqrt{s} = 40$  TeV,  $L = 1033$  cm<sup>2</sup>/sec). In lepton production they showed that one could set an even stronger limit. Calling the quark-lepton coupling

$$L_{q\ell} = n' \frac{g'^2}{\Lambda^2} \bar{q}_L \gamma^\mu q_L \bar{\ell}_L \gamma_\mu \ell_L \quad (2)$$

they found that the SSC could set a limit  $\Lambda' = 40$  TeV, by looking at deviations from QCD predictions for lepton pair production as a function of invariant mass.

At this workshop, we examined several detailed questions in this general framework. We investigated whether momentum resolution, for both leptons and jets, would significantly alter the claims of EHLQ. Following a suggestion of Pilcher,<sup>7</sup> we considered the advantages of varying the beam energy and studying the cross section  $p_\perp^5 d\sigma/d^3p$  at fixed  $x_\perp = 2p_\perp/\sqrt{s}$ . This quantity has the virtue that in the parton model it scales (it is a function of  $x_\perp$  only), while in QCD it is a rather slowly varying function of  $p_\perp$ . If there is a hard component in quark-quark scattering, one should observe quite substantial deviations from scaling. This test should not be as sensitive as the measurement of the absolute rate to one's knowledge of structure functions and higher order corrections. We also examined the deviations in jet angular distributions which might arise from compositeness.

Our group considered two issues of some relevance to machine and detector development. We studied the possible virtues of polarizing the beams and measuring parity-violating asymmetries. This is clearly of value if deviations from QCD predictions are observed, in helping to determine the Lorentz structure of the new interactions. We found that polarization might also improve slightly the limits one could set on  $\Lambda$  from jet cross-sections. In addition, we studied the virtues of photon detection [see also Owens et al., these Proceedings<sup>8</sup>]. We found that, even though the rate is low, since photons represent a relatively clean signal, one should be sensitive to compositeness scales as high as 10 TeV.

Our group examined two issues beyond the framework of flavor-independent contact interactions employed in EHLQ. First we asked: suppose the scale of compositeness is relatively low, say a few TeV. Then one might hope to see some spectacular signatures: structure in cross-sections and multi-quark and lepton production. Reasoning by analogy with QCD, a quite detailed model for these cross-sections was developed (see also Bars<sup>9</sup> and Bars and Albright,<sup>10</sup> these Proceedings). The principle observation is that, since one expects confinement and

formation of flux tubes, a string-like picture with amplitudes similar to those of the Veneziano model should emerge. The resulting model exhibits a great deal of structure, and total cross-sections which grow logarithmically at high energies. It should be useful as an indicator of how finely one can resolve structure at the SSC.

Usually one assumes that the contact interactions are approximately flavor-independent, since this is the simplest way to avoid flavor-changing neutral currents and rare decays. However, it is possible that such processes are avoided by more intricate means, and that the four-fermi interactions exhibit some flavor dependence. This possibility is, in fact, suggested by some models, and should be kept in mind. Members of our group considered possible violations of universality in lepton production, especially in  $\tau$  production (see also G. Snow, these Proceedings<sup>11</sup>).

Abolins et al. considered at some length the properties of possible new particles (exotic quarks and leptons) which might appear in composite models. While we left this subject largely to the Exotics group, we comment here that 3-body decay modes ignored by Abolins et al. are likely to be as important as the 2-body modes they considered.

This contribution is organized into sections, one for each of the topics listed above.

### Effects of Detector Resolution

While discussing the possible contributions of composite models to processes such as  $pp \rightarrow 2\ell^+\ell^-x$ , a question arose concerning the experimental requirements on mass resolution. The worry was that a large error on the mass, when convoluted with the steeply falling Drell-Yan cross section, might mimic and therefore mask additional contributions.

Two comments are immediately in order. First, if the detector resolution is known as a function of mass, then there is no effect, as the resolution can be unfolded from the measured cross-section. Second, in the region of interest, that is high di-lepton masses, the standard cross-section has flattened out slightly.

To see the expected size of possible effects due to detector resolution, we have convoluted the advertised momentum resolution for muons at the SSC ( $\sim 15\%$  at 500 GeV/c, rising linearly to  $\sim 30\%$  at 2000 GeV/c), with the Drell-Yan cross-section  $d\sigma/dM dY|_{Y=0}$  given in EHLQ, Figures 8-16. Without correcting for the mass resolution, the contribution of low masses spilling into the high mass region is such that the integrated cross-section increases by 3% above 1 TeV/c<sup>2</sup> and by 12% above 1.4 TeV/c<sup>2</sup>. Note that even if the mass resolution were a constant 30%, the uncorrected effect in the integrated cross-section would be 22% above 1 TeV/c<sup>2</sup>.

The case of  $pp \rightarrow 2$  jets  $+ x$  may be more interesting in that the total cross-section is larger and it may be more difficult to unfold the detector resolution. Using the cross-section given in EHLQ, Figures 3-22, for jet-pair masses and an energy resolution for jets of 10%, one finds an increase in the uncorrected integrated cross-section of 17% above 5 TeV/c<sup>2</sup>. If the jet-pair mass resolution is as bad as 20%, then the uncorrected integrated cross-section is increased by 54%.

EHLQ suggested that one search for compositeness by looking for a factor of two deviation from QCD predictions. If one imposes such a criterion in practice, it appears that detector resolution is not likely to be a serious limitation in searching for compositeness.

### Scaling Violations in $x_{\perp}$

The methods which have been discussed for looking for contact interactions all involve looking for deviations from QCD predictions. For example, EHLQ suggest looking for increases of a factor of two in single jet and lepton pair production. One might worry that there are uncertainties in the QCD predictions of this order, coming from higher order terms in the perturbation expansion and from uncertainties in the structure functions. It is widely believed that, by the time the SSC turns on, the structure functions will be known over the required  $x$  and  $Q^2$  range to better than 20%.

To get some notion of the size of higher order QCD effects, we performed a simple exercise. We computed the single jet cross-sections, as in EHLQ, as a function of  $p_{\perp}$  at  $y=0$ . But, instead of taking  $Q^2 = p_{\perp}^2$ , for the argument of the structure functions and the couplings, as in EHLQ, we took  $Q^2 = p_{\perp}^2/4$ . This led to changes in the cross-section of no more than 25% over the  $p_{\perp}$  range of interest. Thus, the criteria employed by EHLQ for establishing the existence of contact terms are probably reasonable.

An alternative approach for searching for contact terms has been suggested by Pilcher.<sup>7</sup> In the naive parton model, the quantity  $p_{\perp}^3 \frac{d\sigma}{dp_{\perp} dy}$  is a function only of  $x_{\perp} = 2p_{\perp}/\sqrt{s}$ . In QCD, this scaling behavior is slightly modified due to the  $Q^2$ -dependence of the coupling constant and structure functions. In the multi-TeV range relevant to the SSC, roughly

$$p_{\perp}^3 \frac{d\sigma}{dp_{\perp} dy} \sim p^{-.4} f(x) \quad (3)$$

(See Figure 1, below)

Of course, if contact terms are present, there should be dramatic deviations from scaling as we approach the scale  $\Lambda$ . Observations of such scaling violation might be more convincing than simple deviations in the raw rate. With this in mind, we have plotted  $p_{\perp}^{3.4} d^2\sigma/dp_{\perp} dy$  vs.  $x_{\perp}$  in Fig. 1, using the contact term in EHLQ (Eq. 1) with  $n=-1$ , and  $\Lambda=25$  TeV, as well as the pure QCD prediction, for several values of the beam energy.

The data points represent  $x_{\perp}$  bins of 0.04 per unit of rapidity. At  $x_{\perp}=0.28$ , there are approximately 200 events per bin for an integrated luminosity of  $10^{40}$ . The scaling violations are quite dramatic, so this technique could provide convincing evidence of contact interactions, to rather large values of  $\Lambda$ .

Clearly one concern will be the linearity of the detectors over the wide range in  $p_{\perp}$  required (0.5-6 TeV). It would obviously be desirable to run at several energies so as to minimize such systematic uncertainties.

### Angular Distributions

If deviations from QCD predictions for jet cross-sections are observed, one will want to obtain as much information as possible about their underlying cause. One might hope, from jet angular distributions, to provide further evidence for contact interactions, and to learn about the form of these interactions. In Fig. 2, we have plotted the jet cross-section for pure QCD, at  $y_{\text{boost}} = 1/2(y_1 + y_2) = 0$ , as a function of  $y^* = 1/2(y_1 - y_2)$ . In Fig. 3, we have plotted the same quantity with two forms for the contact interaction. One is the pure left interaction of Eq. (1); the second is a pure vector interaction, (Please see next page)

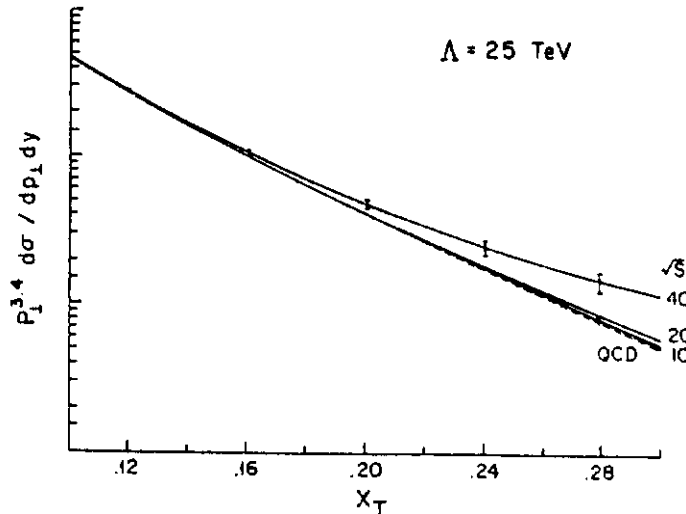


Figure 1. Predictions for  $p_{\perp}^{3.4} d\sigma/dy dp_{\perp}$  vs.  $x_{\perp}$  for different values of  $s$ .



$$L_{VV} = \frac{1}{2} \frac{g^2}{\Lambda^2} n \bar{q} \gamma^\mu q \bar{q} \gamma_\mu q \quad (4)$$

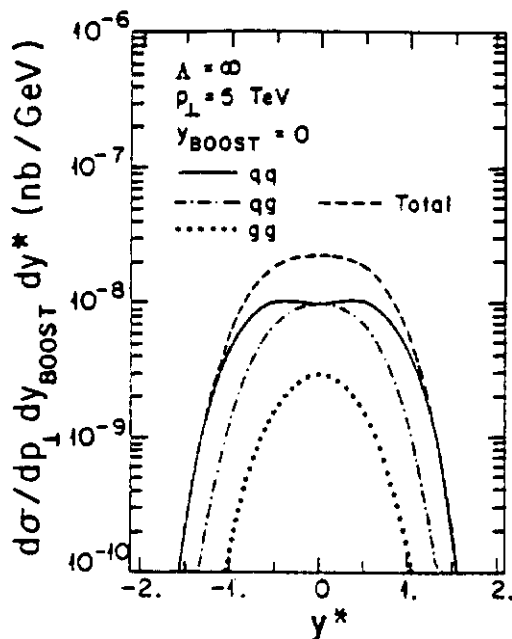


Figure 2. Prediction for  $d\sigma/dy^* dp_T$  for  $y_{\text{boost}} = 0$ ,  $\Lambda = \infty$ .

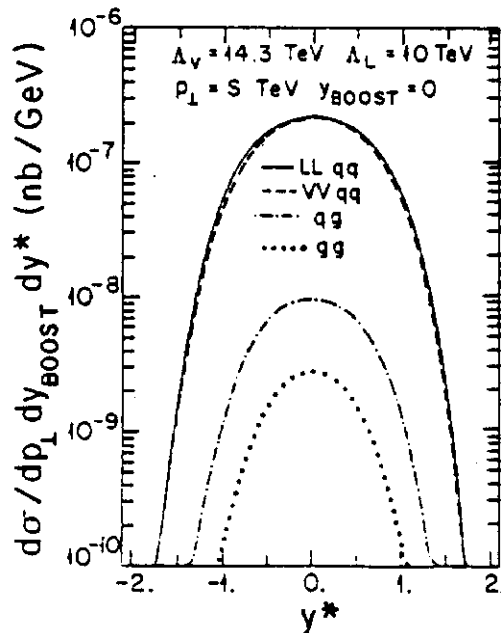


Figure 3. Same as Figure 2, with two types of contact interaction.

so that the curves will coincide, we have taken  $\Lambda = 10$  TeV for the first case;  $\Lambda = 14.3$  TeV for the second. In both cases,  $p_T = 5$  TeV/c, and  $\eta = -1$ .

As one may see from the figures, the QCD distribution is distinctly flatter than the distribution in the presence of contact interactions. Unfortunately, the angular distributions for the LL and VV cases are virtually identical. This is also true for  $\eta = +1$  (not shown). Thus, angular distributions are likely to provide further evidence of compositeness, but probably won't be too helpful in determining the form of the underlying contact interactions.

### Polarization

Any new interactions binding preons into quarks are almost certainly parity violating. Thus, one might hope to get a handle on composite structure by searching for parity violation beyond that expected from electroweak interactions. In particular, parity violating asymmetries in polarized pp scattering would be a useful tool in searching for and disentangling any composite structure.

There are two ways in which polarized beams could play a role in exploring compositeness. First, if significant deviations from QCD predictions for, e.g., jet cross-sections are observed, polarization could help determine the structure of the corresponding contact interactions. Obviously, if we had polarized quark beams, this would be rather easy. However, even in the real world of polarized protons, a good deal is known about the parton structure functions for different helicities, so it should be possible to determine a good deal about the helicity structure of the underlying interactions.

One might also hope that polarized beams would increase one's sensitivity to composite structure altogether. In particular, one might hope to set larger limits on  $\Lambda$  than one can set by looking at, say, the inclusive single jet rate. Such a study, for CBA energies, has been performed by Paige and Tannenbaum.<sup>12</sup> We have scaled this computation up to SSC energies.

The key to our analysis is a result due to D. Hochberg,<sup>13</sup> who has studied extensively the spin-dependent Altarelli-Parisi equations. He has found that, to a good approximation, a prescription due to Carlitz and Kaur<sup>14</sup> for obtaining polarized structure functions from unpolarized ones commutes with QCD evolution. In other words, we may take the distribution functions given by EHLQ at a given  $Q^2$ , and operate on them with the Karlitz-Kaur prescription to find the polarized structure functions at that  $Q^2$ . In fact, following Paige and Tannenbaum,<sup>12</sup> we used an even simpler prescription, obtaining the structure functions from SU(6) relations. Thus,

$$\begin{aligned} u_{++} &= 5/6 u & u_{-+} &= 1/6 u \\ d_{++} &= 1/3 d & d_{-+} &= 2/3 d \end{aligned} \quad (5)$$

Here the first subscript denotes the quark helicity, while the second denotes the proton helicity.

In order to compute the electroweak contribution to the asymmetry, we used the results of Ranft and Ranft,<sup>15</sup> who have computed the relevant QCD-electroweak interference terms. For the compositeness contribution, we take the same interaction as in EHLQ, Eq. (1). This interaction is pure LL; thus it vanishes for all incoming quark polarizations except left-handed quarks on left-handed quarks. We have computed the quantity

$$\Delta = \frac{\frac{d\sigma^{++}}{dp_{\perp} dy} - \frac{d\sigma^{--}}{dp_{\perp} dy}}{\frac{d\sigma}{dp_{\perp} dy}} \quad (6)$$

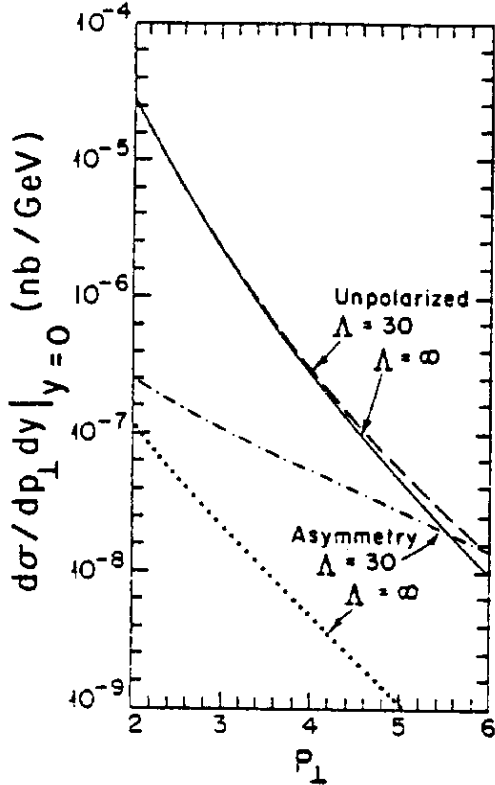


Figure 4. Parity violating asymmetries for the standard model and the contact term with  $\Lambda = 30$  TeV.

The results are shown in Fig. 4, above, for  $\Lambda = 30$  TeV. In order to determine what limits one might set on  $\Lambda$ , we have tried to develop a criterion similar to that of EHLQ. First, we note that, in the absence of compositeness,  $\Delta$  turns out to be less than 10% over the entire range of  $p_{\perp}$ . To be conservative, we require that  $\Delta$  be larger than 20%. Following EHLQ, we also require that there be at least an excess of 50 events in a 100 GeV bin in  $p_{\perp}$ , for an integrated luminosity of  $10^{40} \text{ cm}^2$ . Then we find that one can set a limit of 30 GeV on  $\Lambda$ . This is compared with the 20 GeV limit from jets (and the 40 GeV limit from lepton pairs) suggested by EHLQ. If one requires that there be an excess of 50 events in all momentum bins above a certain value, one does not improve the limit significantly.

Thus, polarization slightly improves the limits one can set on  $\Lambda$  over those from jets, but one can still obtain a better limit from lepton pairs. Further

detailed study of how well one can do in disentangling the various types of contact interactions would certainly be desirable. As a simple, but interesting, example, note that the asymmetry (6) is equal in magnitude and opposite in sign for pure left-left and pure right-right interactions.

### Direct Photons

Direct photons at high  $p_{\perp}$  are clearly interesting probes of quark-quark interactions, and they have been the subject of some interest at this conference (see, e.g., G. Feldman, these Proceedings<sup>16</sup>). Clearly, if quarks show structure on SSC energy scales, the single  $\gamma$  production cross-section will be harder than expected from QCD. This issue was considered by members of our group and a detailed discussion appears in these Proceedings. Here we will just summarize the major findings.<sup>8</sup> In QCD, the principal source of direct photons is a Compton-like process, in which a gluon scatters from a quark, which emits a photon. Bremsstrahlung processes also make a sizable contribution, though this falls rapidly at large  $p_{\perp}$ . If quarks are composite, there will be additional contributions. These can be described, for  $p_{\perp} \ll \Lambda$ , by contact interactions. The lowest dimension operators which can contribute have the form

$$e_{UVDO} \frac{e F_{UV}^{\gamma}}{\Lambda^2} \bar{q} D_{\mu} \gamma_{\sigma} q \quad (7)$$

where  $D_{\mu}$  is the covariant derivative (and thus includes a gluon coupling). Such an interaction would arise, for example, from production of an off-shell, excited fermion. This gives a contribution to the amplitude for  $qq + \gamma q$  of size  $\hat{s}/\Lambda^2$  relative to the QCD contribution, and thus dominates once the subprocess energies are of order  $\Lambda$ . For  $\hat{s} > \Lambda^2$ , we would expect the cross-section to become roughly constant, of order a times the total cross-section. Of course, it might exhibit interesting structures, such as resonances, on scales of order  $\Lambda$ .

Because photons are comparatively clean, one can tolerate relatively low rates. From QCD alone, Owens et al. find that with  $p_{\perp} = 3$  TeV there are about 54 events in a 1/2 TeV bin per year. If  $\Lambda = 10$ , using the contact interaction above, this number is about doubled. So, direct photons can provide access to scales of about 10 TeV.

### Crossing the Compositeness Scale

It is possible that the scale of compositeness is only a few TeV. In that case, at high transverse momenta the quarks and leptons should appear as strongly interacting particles. Their cross-section should exhibit structure, such as resonances, and presumably will tend to a constant, geometrical value, of order  $10\pi/\Lambda^2$  for quark-quark scattering, and of order  $\alpha_s$  times smaller for gluon-quark scattering. Multiple  $\gamma$  quark and lepton production should be common, with multiplicity distributions similar to those of conventional hadron physics.

Such a situation, at the SSC, should be quite striking. Of course, since we don't have monochromatic quark beams, it is natural to ask how much of this structure we will be able to resolve. Towards this end, a quite detailed model for quark-quark and quark-gluon scattering was developed. We refer the interested reader to the work of Bars<sup>9</sup> and Albright and Bars<sup>10</sup> for the details, and summarize the principle results here.

As discussed in the Introduction, we expect the dynamics of the underlying preon theory to be similar, in many respects, to that of QCD. In particular,

we expect confinement, described by pre-color flux tubes. Thus, composite fermions and bosons might well lie on linear Regge trajectories, reflecting approximate string dynamics. The major difference from QCD is that the preon theory necessarily has (almost) massless fermions (the quarks and leptons), rather than massless pions. Also, to explain the lightness of the quarks and leptons, the preon theory must have a high degree of unbroken symmetry, so the spectrum should show large, approximate degeneracies. Using Regge Pole and duality arguments, and making some simplifying assumptions about the spectrum, a detailed model with a great deal of structure was constructed in this way, for both quark-quark and gluon-quark scattering. Note that gluon-quark and gluon-gluon scattering may be quite important if the scale of compositeness is small, since the gluon distributions are so large at low  $x$ .

For reasons of time, we have not been able to produce results for these detailed models. Of course, it is not clear how much detailed structure will be visible once the cross-sections are folded with the parton distributions. One case where a similar type of structure has been considered for the SSC is technicolor. There, EHLQ<sup>2</sup> have included techni-vector mesons in certain production cross-sections. Not much structure survives; these resonances appear as broad enhancements, if at all (see, e.g., EHLQ, Figs. 6.10 - 6.13).

In our case, some care will have to be taken in how data is plotted. For example, jet cross-sections at fixed  $m^2$  integrated over  $p_{\perp}$  and  $y^*$  blow up, due to the QCD contribution which blows up at  $t=0$ . So, one may wish to plot cross-sections as a function of  $m^2$  with a lower cutoff on  $p_{\perp}$ , or as functions of  $p_{\perp}$ , or in some other way. As a simple first exercise, we did the following:

We assumed a neutral resonance in the s-channel, of mass  $\Lambda$ , width  $\Lambda/s$ , and coupling  $g$ . We plotted  $d\sigma/dM dy$ , with a cutoff on  $p_{\perp}$ , for various values of  $\Lambda$ . Also, to avoid being swamped by gluons, we included only the quark-antiquark component of the cross-section. For  $\Lambda = 3-6$  TeV, and  $p_{\perp \text{ min}} = 0.5-2$  TeV, no structure was visible in the cross-section. This is clearly an area for further work, however. Perhaps more ingenious cuts, or focusing on leptons, can enhance structure.

#### Compositeness in the $\tau\bar{\tau}$ Channel

Among the principle attractions of compositeness are that it might explain the generation puzzle and the origin of quark and lepton masses. If compositeness is somehow tied to the breaking of  $SU(2) \times U(1)$  (as in extended technicolor), then scales of order a few TeV may be contemplated. The major constraint on such ideas comes from rare processes. Large suppressions of strangeness changing and lepton number violating processes must somehow be arranged. This can occur if the theory has, in some approximation, a very high degree of symmetry among the generations. For example, in EHLQ, it was assumed that the four-fermi interactions are flavor blind; this automatically conserves all quark and lepton flavors. However, it is not easy to construct models with so much symmetry.<sup>6</sup>

Thus, if compositeness occurs at scales less than 40 TeV, rare processes might be avoided by some more intricate means.

With this in mind, George Snow considered the possibility that compositeness leads to a significant enhancement of  $\tau$  pair production, but not much additional  $e$  or  $\mu$  production. This idea was motivated by two classes of models. One, due to Pati,<sup>17</sup> in which there is a lower compositeness scale for heavy quarks and leptons than light ones; one, due to Bars,<sup>9</sup> in which the  $\tau$ 's are in the same family as the  $u$  and  $d$  quarks. In the first case, the principle four-fermi terms couple  $b$  and  $t$

quarks to  $\tau$  leptons; in the second they couple  $u$  and  $d$  quarks to  $\tau$  leptons, with  $e$  and  $\mu$  couplings suppressed by mixing angles. No matter how seriously one entertains either class of models, it is clearly quite important to keep in mind the possibility of some non-trivial flavor dependence and violations of universality, and  $\tau$  identification is thus desirable.

Most of Snow's calculations (performed in collaboration with K. Lane) are for the Pati-type model. For the Bars-type model, one can determine the rates as a function of mixing angles simply by examining Fig. 8-16 in EHLQ, and multiplying by any assumed mixing angle. With interaction

$$L = \frac{4\pi}{\Lambda^2} n \left[ \bar{b}_L \gamma_{\mu} b_L \bar{\tau}_L \gamma^{\mu} \tau_L + \bar{t}_L \gamma_{\mu} t_L \bar{\tau}_L \gamma^{\mu} \tau_L \right] \quad (8)$$

Snow finds that, for  $\Lambda = 4.5$  TeV, the cross-section is  $\frac{d\sigma}{dy}|_{y=0} = 1.1 \times 10^{-5}$  nb, a factor of ten larger than the pure QCD rate.  $\tau$ 's may not be too hard to detect, because of the low multiplicities of their decay products. After considering various backgrounds, Snow concludes that a factor of ten enhancement in the  $\tau$ -signal is detectable, so that in models of this type,  $\Lambda$ 's up to about 5 are detectable.

Determining, more generally, the sensitivity of the SSC to violations of universality will depend clearly on how well one understands the detection efficiency for  $e$ 's,  $\mu$ 's, and  $\tau$ 's.

#### New Particles Predicted by Composite Models

While no truly complete or compelling model of composite quarks and leptons currently exists, many of the toy models which have been studied,<sup>1</sup> as well as the classification of models by Bars,<sup>6</sup> suggest that such a theory might contain relatively light exotic states: colored particles with lepton number, color sextets, and so on. (Of course, among the highly excited states, there will certainly be excitations with such quantum numbers. Here we are interested in states with masses below  $\Lambda$ .) The production and decays of such particles can be analyzed in the same fashion as hard quark scattering. One writes down operators of the lowest dimension which can produce the desired decay and which obey the conjectured symmetries. This topic was the subject of extensive discussion in the 1982 Snowmass Proceedings, and also in the Exotics group at this conference. We wish to add only one point to those discussions:

It is usually assumed that the decays of such exotics occur through magnetic moment-type couplings. However, the four-fermi operators whose role was so heavily stressed by Abolins et al.<sup>3</sup> for scattering seem likely to be equally important here. First, there is not likely to be any particular suppression due to quantum numbers. For almost any conceivable exotic, there is some conventional three-body final state with correct helicity, color, and lepton number. Second, just as the coupling  $g^2/4\pi$  enhances the four-fermi operators over the form factors in hard quark scattering, so this factor, in decays, compensates for the extra suppression due to three-body phase space. In general, then, we would advise those considering exotic decays to be mindful that three-body final states are likely to be as important as two-body states.

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# NEW PHYSICS SIGNATURES IN POLARIZED e-e+ EXPERIMENTS \*

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## ABSTRACT

In e-e+ experiments with the e- beam transversely polarized we compute an asymmetry and show that in the near future it can serve as a probe of "new physics" up to scales of order 20 TeV. The asymmetry is proportional to the mass of the final state fermion and hence is largest in the production of the top quark (unless there exists a heavier fermion). There is practically no standard model background to this asymmetry. For example, at center of mass energies of 120 GeV and fermion mass of 42 GeV, compositeness scales of 5,10,15,20 TeV yield asymmetries of 14.4%, 3.8%, 1.7%, 0.9% respectively. We have also found substantial deviations in the unpolarized cross sections. For example at 200 GeV and  $\cos\theta = -0.7$  this deviation is estimated as 35.5%, 50%, 19%, 10% at the above compositeness scales. Our general analysis is applicable to other "new physics" as well.

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As the search for "new physics" beyond the standard model continues, e-e- machines play an important role mainly because the fundamental interactions are more directly reached via leptons. It was shown that interference between old and (TeV-range) new physics amplitudes can be sufficiently large to be detectable at the SLC and LEP [1]. By using polarized beams we showed that the sensitivity of  $E < 100$  GeV machines to new physics can be pushed as far as  $M = 4-7$  TeV in the case of compositeness [2]. LEP-II would reach much higher.

In the present discussion we will concentrate also on compositeness for definiteness. But we would like to emphasize that our approach and computation would apply to other types of new physics as well.

In this paper we propose a new and more sensitive test of "new physics" relative to refs.1-2. We compute an asymmetry which probes an invariant amplitude that cannot be reached by the type of experiments discussed in refs. 1-2. We show that with one transversely polarized electron beam it is possible to define model independent asymmetries in which the standard model background is practically non-existent. We find that the magnitude of the asymmetry is approximated by  $(m_f^2/E^2 A)$  x (energy and angle dependent factors defined below), where  $m_f$  is the mass of the heaviest quark or lepton that can be produced in pairs at a given energy E, A is a typical standard model amplitude comparable to photon or Z exchange,  $B = g^2/N^2$  is a "new physics" amplitude, where N is the scale for new physics. Let us take  $m_f \sim 42$  GeV as a typical value. Then the "new physics" contributions to this asymmetry remains larger

than the negligible standard model background up to scales as high as  $M=500$  TeV (for a new strong interaction  $g^2 \approx 10$ , like compositeness).

At  $E=100-200$  GeV, and compositeness scales of  $M=5/30$  TeV the maximum asymmetry occurs in the neighborhood of the scattering angles shown below

$\cos\theta$	$E \setminus M$	5	10	15	20	25	30
-.4	100	.015	.003	.001	"0"	"0"	"0"
-.7	110	.060	.015	.007	.004	.002	.001
-.8	120	.144	.038	.017	.009	.006	.004
-.8	150	.325	.112	.050	.028	.018	.012
-.7	200	.293	.147	.069	.039	.024	.017

It is evident that the asymmetry is fairly large even at the higher scales. Of course, for the larger energies higher values than  $m_f \approx 42$  GeV could be considered and this would yield some increase in the expected asymmetries at energies  $E > 2m_f$ . This would apply if the top quark is heavier or if there are 4<sup>th</sup> generation quarks or leptons. At smaller energies the b-quark is the heaviest that can be produced. Then the asymmetry is largest around 58 GeV and is approximately 3.5%, 0.9%, 0.4%, 0.2% at compositeness scales  $M=5, 10, 15, 20$  TeV respectively. It is negligible at the  $Z^0$  resonance.

In this paper we shall also discuss deviations in the unpolarized cross sections, which as will be seen below provide a probe for a different set of invariant amplitudes as compared to the polarization asymmetry above. For the larger energies attainable at LEP-II the

deviations from the standard model are measurably large up to compositeness scales of 20 TeV.

These tests provide information that sets the stage and the mood for the next generation of experiments that can be performed at hadronic machines such as the SSC which can reach as far as 100 TeV as explored elsewhere [3,4,5]. This suggests that accurate polarization and high luminosities in e<sup>+</sup>e<sup>-</sup> machines are probably extremely important investments for future discovery of "new physics".

We note that, the measurement of such asymmetries is limited by the accuracy of the polarization and by statistical errors. With anticipated luminosities at the SLC and LEP (I and II) it appears possible to detect compositeness up to scales of the order 20 TeV provided, of course, that the polarization of a transversely polarized electron beam is known accurately and systematic errors can be controlled. In addition, it should be emphasized that the asymmetries and cross section deviations that we have computed assume that the final state containing the heavy fermion-antifermion pair can be distinguished from other, lower mass, final states. If not, these other final states will dilute the asymmetries, but not necessarily the cross section deviations. Furthermore, since the angular dependence of the asymmetries and deviations will be important tools probing different invariant amplitudes (see below), it is vital that the heavy fermion pair jet axis be determinable with reasonable accuracy.

We now describe our calculation.

Although many polarization studies exist in the literature [6,7]

we have not found any which was sufficiently general to include all the independent (and crucial) amplitudes defined below and that also paid sufficient care to the mass and spin dependence of all external fermions in the reaction  $e^+e^- \rightarrow f\bar{f}$  for any final fermion  $f$ . To fill this gap, we have analytically computed the cross section for the general 4-fermion process  $f_1 f_2 \rightarrow f_3 f_4$  with arbitrary masses and spins for each fermion, including the most general 10 independent amplitudes as allowed by Poincare invariance (partly not conserved). It is useful to work in a chiral (rather than helicity) basis because, except for the negligible Higgs interactions, all standard model vertices conserve chirality. Then, up to Fierz transformations, any amplitude can be written in the model independent form [8]

$$A(f_1 f_2 \rightarrow f_3 f_4) = [A_{LL} \bar{u}_{3L} \gamma^\mu u_{1L} \bar{v}_{2L} \gamma^\nu v_{4L} + B_{LR} \bar{u}_{3L} \gamma^\mu u_{1L} \bar{v}_{2R} \gamma^\nu v_{4R} \\ - C_{LR} \bar{u}_{3L} \gamma^\mu v_{4L} \bar{v}_{2R} \gamma^\nu u_{1R} + D_{LR} \bar{u}_{3L} \gamma^\mu u_{1R} \bar{v}_{2L} \gamma^\nu v_{4R} \\ + E_{LR} \bar{u}_{3L} \gamma^\mu v_{4R} \bar{v}_{2L} \gamma^\nu u_{1R}] + [L \leftrightarrow R]$$

The tedious task of squaring and performing the traces can be done efficiently by using certain unfamiliar trace identities [9][1]. The mass dependence enters through the fermion projection operators  $\frac{1}{2}(1+\gamma_5)$  and  $\frac{1}{2}(1-\gamma_5)$ . The details and the compact exact result of this general calculation will be reported elsewhere [9]. Here we will limit ourselves to only a transversely polarized electron beam and set  $D_{LR}=D_{RL}=E_{LR}=E_{RL}=0$ , because these chirality breaking amplitudes are totally negligible compared to the chirality conserving "new physics" contributions to the  $A, B, C$  amplitudes [12,13] (in ref.9 all  $A, B, C, D, E$  and

all spins and masses are kept).

The crucial "new physics" amplitudes are  $B_{LR}$  and  $B_{RL}$ . For  $e^+e^- \rightarrow f\bar{f}$  (with  $f$  not  $e$ ), photon,  $Z$ ,  $W$  or gluon exchange to any order cannot

contribute to the  $B$  amplitudes because of the chirality and family conserving structure of these interactions in the standard model. Furthermore, the chirality violating Higgs contributes in negligible amounts [12]. Therefore, the  $B$  amplitudes are essentially zero in the standard model. Thus, a larger  $B$ -amplitude is possible only from chirality conserving new physics sources, as e.g. in compositeness or family changing interactions [13,14]. Although, as argued here, the "vanishing" of  $B$  is a simple fact in the standard model, it does not seem to be generally appreciated, perhaps because of the tendency to use helicity [6,7] rather than chirality [8] amplitudes (e.g. ref. 7 concentrates on chirality breaking physics and misses the chirality conserving  $B$ ).

As pointed out in ref.2, one ideal experiment that would exploit the  $B$  amplitudes needs 100% longitudinally polarized  $e^+e^-$  beams with opposite helicities. Any non-zero cross section in such an experiment is necessarily due to new physics since only  $B$  contributes (neglecting the Higgs contributions). Unfortunately, it is impossible to perform such an experiment with presently known techniques. Instead, we explored deviations from standard model cross sections with partially polarized beams [2]. In that analysis, in addition to  $B$ , the "new physics" contributes to the  $A, C$  amplitudes as well. It is the corrections to  $A, C$  that dominated the deviations from the standard model in the polarized

cross sections of ref 2. In this paper we will explore an asymmetry which is proportional to B (apart from negligible terms proportional to  $|A|^2$ ,  $|C|^2$  or AC times powers of the electron mass), and hence provide a new, different and more sensitive probe of "new physics". The experiment requires only a transversely polarized electron beam, and the asymmetry is obtained by reversing the polarization. The polarization need not be 100%, but must be known rather accurately so that errors do not overwhelm the signal.

For the reaction  $e-e^+ \rightarrow f\bar{f}$  we define the asymmetry as the ratio  $A_{SY} = \{[+] - [-]\} / \{[+] + [-]\}$ , where  $[\pm]/16\pi E^4$  represent the differential cross sections  $d\sigma/dt(\pm)$ , for a transversely polarized electron beam with opposite signs of the polarization. Our calculation yields

$$\begin{aligned} \{[+] - [-]\} = & 8m_f p_1 \cdot p_2 s_1 \cdot p_4 \text{Re}(A_{LL} + C_{RL})B^*_{RL} - (A_{RR} + C_{LR})B^*_{LR}] \\ & + 8m_f \epsilon(p_1, s_1, p_2, p_4) \text{Im}(A_{LL} + C_{RL})B^*_{RL} + (A_{RR} + C_{LR})B^*_{LR}] \\ & + (\text{negligible}) \\ \{[+] + [-]\} = & 8p_1 \cdot p_4 p_2 \cdot p_3 \{ |A_{LL}|^2 + |A_{RR}|^2 \} + 8p_1 \cdot p_2 p_3 \cdot p_4 \{ |B_{LR}|^2 + |B_{RL}|^2 \} \\ & + 8p_1 \cdot p_3 p_2 \cdot p_4 \{ |C_{LR}|^2 + |C_{RL}|^2 \} + (\text{negligible}). \end{aligned}$$

Here  $\epsilon(a b c d)$  is the Levy-Civita tensor contracted with the momenta  $a, b, c, d$ ,  $m_f$  is the mass of the final fermion,  $p_i$  are the momenta and  $s_i$  is the spin of the electron. Neglecting the mass of the electron, we may parametrize these in terms of the center of mass energy  $E$  as  $p_1 = [E/2, 0, 0, E/2]$ ,  $p_2 = [E/2, 0, 0, -E/2]$ ,  $p_3 = [E/2, q \sin\theta, 0, q \cos\theta]$ ,  $p_4 = [E/2, -q \sin\theta, 0, -q \cos\theta]$ ,  $s_1 = [0, P \cos\phi, P \sin\phi, 0]$ , where

$q = [(E/2)^2 - m_f^2]^{1/2}$  and  $P$  is the amount of polarization. The neglected terms in the cross sections are all proportional to one, two or three powers of the electron mass. At  $E = 100$  GeV the largest of these is of the order of  $(m_e \Lambda / m_f B) \approx (M/500 \text{ TeV})^2$  times the  $|B|^2$  terms in the combination or times the AB terms in the - combination. Thus for compositeness scale of  $M = 10 \text{ TeV}$ , the neglected terms are smaller by a factor of at least  $10^{-4}$ . The details of all terms, without any approximations are found in ref. 9. One important observation is that our result is proportional to the final fermion mass, so that we will get the largest signal from the production of the heaviest available fermion, presumably the top quark, (unless a fourth generation exists)

Let us define the  $A$  and  $C$  amplitudes. Apart from "new physics" contributions, they correspond to top quark production via photon and Z exchange in the s-channel, and are given by

$$\begin{aligned} A_{LL} &= e^2 [Q_e Q_t / E^2 + L_e L_t / (E^2 - m_Z^2 + i m_Z \Gamma_Z)] + [\text{new physics}] \\ A_{RR} &= e^2 [Q_e Q_t / E^2 + R_e R_t / (E^2 - m_Z^2 + i m_Z \Gamma_Z)] + [\text{new physics}] \\ C_{LR} &= e^2 [Q_e Q_t / E^2 + R_e L_t / (E^2 - m_Z^2 + i m_Z \Gamma_Z)] + [\text{new physics}] \\ C_{RL} &= e^2 [Q_e Q_t / E^2 + L_e R_t / (E^2 - m_Z^2 + i m_Z \Gamma_Z)] + [\text{new physics}] \end{aligned}$$

where  $Q_e = -1$ ,  $Q_t = 2/3$ ,  $L_e = (2 \sin^2 \theta_W - 1) / \sin 2\theta_W$ ,  $R_e = 2 \sin^2 \theta_W / \sin 2\theta_W$ ,  $L_t = (1 - 4/3 \sin^2 \theta_W) / \sin 2\theta_W$ ,  $R_t = 4/3 \sin \theta_W / \sin 2\theta_W$ . A similar expression applies to b-quark production at lower energies, with  $L_b$ ,  $R_b$ ,  $Q_b$  replacing  $L_t$ ,  $R_t$ ,  $Q_t$  respectively. For the "new physics" amplitudes  $B$  we specialize to a 4-fermi contact term of the form  $B_{LR} = b_{LR} (20/M^2)$  and  $B_{RL} = b_{RL} (20/M^2)$ , where  $M$  is the compositeness scale. The factor



of order 20 corresponds to a strong interaction strength ( $g^2/4\pi \approx 1$ ) times a diagram counting factor of 2 [2,4,8]. The remaining model dependent factors  $b_{LR}$  and  $b_{RL}$  are of order one and are inserted to represent the possibility of parity violation [2]. Thus, we take  $r=b_{RL}/b_{LR}$  and  $b_{LR}^2+b_{RL}^2=2$ , with  $r$  arbitrary in sign and magnitude.  $r=+1$  corresponds to parity conserving "new physics". In a composite model it is natural to expect  $r$  different than 1.

We are now in a position to estimate the asymmetry numerically. We will assume at first that the A and C amplitudes are just the standard model amplitudes and look only at the effects of the B amplitudes. Later we will return to the cross section which is much more sensitive to  $A, C$ . The inclusion of the compositeness effects in  $A, C$  for various models changes our estimated values of the asymmetry below by a factor  $\sim (1 \pm 0.25)$  at  $M=5$  TeV, and by negligible amounts at  $M=10, 15, 20$  TeV. We assume that  $P \cos \phi = 1$ ,  $r = 0$ , and use  $m_b = 4.2$  GeV,  $\sin^2 \theta_W = 0.222$ . Then for  $E=100, 110, 120, 150, 200$  GeV, we obtain approximately

$$A_{sy}(E) = \frac{(5 \text{ TeV}/M)^2 \sin \theta}{\alpha (1+v \cos \theta)^2 + \gamma (1-v \cos \theta)^2 + \beta (5 \text{ TeV}/M)^2}$$

where  $v = [1 - (2m_f/E)^2]^{1/2}$  is the velocity of the outgoing fermion, and the energy dependent coefficients  $\alpha, \beta, \gamma$  are

E	v	$\alpha$	$\beta$	$\gamma$
100	0.542	57.3	0.103	15.20
110	0.645	22.9	0.177	2.023
120	0.714	14.4	0.252	0.515
150	0.828	7.15	0.542	0.177
200	0.907	4.17	1.349	0.215

At the Z resonance, with  $m_Z = 92$ ,  $\Gamma_Z = 2.9$  GeV,  $P \sin \theta = 1$ ,  $r = 0$ , we obtain approximately

$$A_{sy}(92) = (0.24 \text{ TeV}/M)^2 \sin \theta / [(1 + 0.41 \cos \theta)^2 + 0.73(1 - 0.41 \cos \theta)^2]$$

At lower energies the b-quark is the heaviest fermion that can be produced. Then the largest asymmetries occur around  $E=58$  GeV. Using  $m_b = 5$  GeV,  $P \cos \phi = 1$ ,  $r = 0$ , we obtain

$$A_{sy}(58) = (0.74 \text{ TeV}/M)^2 \sin \theta / [0.13 (1 + 0.985 \cos \theta)^2 + (1 - 0.985 \cos \theta)^2]$$

The maximum asymmetries given earlier in our paper follow from these approximate expressions. At other values of the parameters our general formula provides the answer.

We now turn to the effects of "new physics" through the  $A, C$  amplitudes. The "new physics" parts of the  $A, C$  amplitudes above are, within factors of order 1, similar in magnitude to the B amplitudes and could differ in sign in a model dependent way [2]. In the cross sections  $[+]$  or  $[-]$  the cross terms between "new" and "standard" model contributions dominate the deviations. While we could analyze a number of polarization dependent effects, here we will concentrate on the unpolarized cross section. We define the deviation from the standard model as

$$\text{dev}(E, \theta, M) = \{[+] + [-]\} / \{[+] + [-]\}_0 - 1$$

where the subscript "0" indicates pure standard model amplitudes. As an

example we take "new physics" contributions  $\Delta A_{LL} = \Delta A_{RR} = \Delta C_{LR} = \Delta C_{RL} = 20/M^2$ , i.e. the same as the B amplitude. Rather than a full display of the angular dependence we give the numerical estimates at the value of  $\cos\theta$  where the asymmetry (not the deviation in cross section) becomes a maximum. The deviations are actually even larger in the backward direction, and decrease to much smaller values in the forward direction. The reason for choosing this value of  $\cos\theta$  is to provide a comparison between these two sensitive probes at the same angles that appeared in the asymmetry table above. For  $E=100-200$  GeV and  $M=5-30$  we obtain the deviations shown below.

$\cos\theta$	$E \setminus M$	5	10	15	20	25	30
-4	100	-.003	-.001	-.001	"0"	"0"	"0"
-7	110	-.017	-.010	-.005	-.003	-.002	-.001
-8	120	.077	-.003	-.003	-.002	-.002	-.001
-8	150	1.35	.192	.074	.039	.024	.017
-7	200	3.55	.49	.185	.098	.061	.041

We see that the deviations become most significant at the higher energies. These deviations in the unpolarized cross section are substantial signals of new physics activity mainly in the  $A, C$  amplitudes. However, we note that the systematic error in measuring the overall normalization of the cross section is likely to be significant and therefore it is preferable to measure ratios of cross sections, as in asymmetries.

It is straightforward to apply our general approach to other "new physics". One simply needs the B amplitude for the new phenomenon. We

emphasize that our theoretical analysis is rather model independent. The specific model determines the parameters that define B and the corrections to A, C.

In summary, we have pointed out that there exists an asymmetry with a practically vanishing standard model background. Experimentally, we need a transversely polarized electron beam and measure cross sections with reversed polarizations. The combined measurements of the unpolarized cross sections and asymmetries can probe up to a "new physics" scale of 20 TeV. These two types of measurement are complementary and probe different amplitudes of "new physics" (i.e. B versus A, C). For given M both the cross section deviations and asymmetries get larger at higher  $e^+e^-$  energies and hence become easier to measure. At the SLC and LEP-I ( $E \leq 100$  GeV) the asymmetry is measurable but is considerably smaller than at LEP-II ( $E \leq 200$  GeV). For asymmetries, accurate measurement of the beam polarization, identification of heavy fermion states, and high energies and high luminosities are essential to be able to probe the higher "new physics" scales. For cross section deviations, control of systematic errors is critical. Such experiments are very powerful for discovering corrections to the standard model processes, and until the building of the SSC they will probably remain as the best probe for "new physics". Therefore, we urge our experimentalist colleagues to invest in developing the technology needed to perform the type of measurements suggested here.

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## FOOTNOTES

metric convention is -+++

[f1] We give here some useful trace identities

$$\begin{aligned}\text{Tr}[a\gamma^\mu(1\pm\gamma_5)/2] \text{Tr}[b\gamma_\mu(1\pm\gamma_5)/2] &= 2\text{Tr}[ab\tilde{(1\pm\gamma_5)/2}], \\ \text{Tr}[a\gamma^\mu(1\pm\gamma_5)/2] \text{Tr}[b\gamma_\mu(1\mp\gamma_5)/2] &= 2\text{Tr}[ab(1\pm\gamma_5)/2], \\ \text{Tr}[A\gamma^\mu B\gamma_\mu(1\pm\gamma_5)/2] &= 2\text{Tr}[A(1\pm\gamma_5)/2] \text{Tr}[B(1\mp\gamma_5)/2], \\ \text{Tr}[a\gamma_\mu b\gamma^\mu(1\pm\gamma_5)/2] &= -2\text{Tr}[ab\tilde{(1\pm\gamma_5)/2}].\end{aligned}$$

Here a or b are products of odd numbers of gamma matrices and A or B are products of even numbers of them.  $b^\sim$  is the product in reverse order. From these we can derive other useful identities which simplify the calculation tremendously [9].

[f2] We expect that any new physics must preserve chirality to be consistent with massless chiral families at scales larger than 100 GeV. (This is certainly the case in any reasonable composite model).

Therefore, any chirality breaking contribution to these amplitudes is expected to involve at least one power of fermion mass at each vertex. By dimensional arguments some large mass must appear in the denominator at each such vertex, thus producing a negligible contribution. In particular, the Higgs particle contributes with factors of order  $(m_{\text{fermion}}/m_W)$  at each vertex. Since for the case of interest one of these vertices must include the electron mass, we can easily show that these D,E amplitudes are negligible compared to other chirality conserving "new physics" contributions to the A,B,C amplitudes, up to extremely high new physics scales M.

[f3] In a composite model the unbroken preonic chiral transformations may act simultaneously on several composites that share common constituents. Thus, depending on the fermions  $f_1, f_2, f_3, f_4$  the B amplitude is allowed by chiral symmetries in some models while it is forbidden in others. Our asymmetry is nonzero for models in which B is allowed by chiral symmetries. Note that there are always allowed contributions to the A,C amplitudes. The deviations in the unpolarized cross sections reported here depend mainly on the "new physics" contributions to A and/or C and are rather insensitive to B.

[f4] It is possible to find composite models that do not produce  $K^+ \rightarrow \pi^+ \mu e$  or  $K^0 \rightarrow \mu e$ , and allow a compositeness scale in the TeV range.

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COMPOSITE QUARKS AND LEPTONS  
TESTS AND MODELS\*

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The theory and tests of composite quarks and leptons are reviewed. A model that addresses the puzzle of lepton-quark symmetry within a family is presented. A dynamical mass generating mechanism is discussed. The present evidence that requires the compositeness scale to exceed 3 TeV is reviewed and further tests at the SLC, LEPI and LEPII that would be sensitive to scales as large as 20-25 TeV are emphasized. Signals that would correspond to compositeness at SSC energies are described.

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## 1. INTRODUCTION

What motivations do we have for considering compositeness as a possible scenario for new physics beyond the standard model? One obvious motivation is the historical evolution of our understanding of the structure of matter. When a curious listener is presented with the fact that matter is made of atoms which in turn contain nuclei made of protons and neutrons and that these are composites of quarks, he or she is led to ask the inevitable question of whether quarks as well as leptons themselves may contain other "stuff" in them? As physicists we have not reached yet the stage of answering this question. Many of us have suggested preon models for composite structures that are as large as  $10^{-17}cm$  as well as string models that characterize all matter as composed of strings at distances of  $10^{-33}cm$ . These are widely different pictures of the structure of matter. From all available experimental evidence and its theoretical interpretation in terms of the standard model, all we can say is that the quarks and leptons have no visible structure up to distances as small as  $10^{-17}cm$  and that according to accepted theoretical principles it is possible that new structure at around  $10^{-17}cm$  or smaller distances may exist. The accelerator energies required to probe such distances will be available at future planned accelerators and therefore it is imperative that we investigate this question.

The standard model, as presently formulated, is very successful in explaining all known data- except for the 17 parameters it contains and the puzzles associated with the family repetitions as well as the lepton-quark symmetry within a family. In looking for new composite structures beyond the standard model one has the hope that some or all of these phenomena may be explained. That preonic composite models of quarks and leptons have this potential has been emphasized by many authors before [1], and some aspects of how this can happen has been illustrated in various models [e.g. ref 2]. Of course, other approaches are also candidates for explaining the puzzles left open by the standard model, and in particular I should emphasize that superstring theory has provided very attractive theoretical possibilities for solving some of these problems. Some of the string mechanisms that address these questions, without invoking any other composite structures, are more elegant than the ones presented in conventional preon models. Admittedly, string models are presently more attractive to many theorists, including this author, because they hold the promise of providing a fundamental theory of all forces, including quantum gravity. Some hybrid ideas using string and preon mechanisms have also been discussed by a limited group of physicists primarily from Maryland, consisting of Pati and collaborators [3]. In

the absence of experimental clues all of the above ideas remain as speculation. Hopefully the new accelerators will shed some new light and provide much needed experimental guidance.

One weakness of preon ideas is that they rely on scenarios which, at this stage, are hard to verify in confining strongly interacting theories. Therefore, there is disagreement even among experts as to whether a particular scenario is really consistent within the dynamics of the proposed theory (e.g. under what circumstances can we obtain massless composite fermions?). Nevertheless, assuming that only the most general outlines of such an idea are theoretically consistent, preon models, whose scale of confinement is a few TeV, make dramatic predictions that can be tested in coming accelerators.

Although the dynamics of preon models remains somewhat obscure, other features, such as the emergence of symmetries naturally from the kinetic term of the preon Lagrangian, the classification of composites in ways that tend to give family repetitions automatically as a requirement of anomaly cancellation or matching, the absence of the hierarchy problem and the potential for dynamical mechanisms of mass generation are still some attractive features of this approach (see discussion in a later section).

In this talk I will concentrate on certain tests of compositeness that rely only on general properties of the theory of composite quarks and leptons [2,4-10]. Similar as well as additional tests can be found in refs.[3,11-13], but some of these may involve additional assumptions. I will take the  $W^\pm, Z$  as elementary, at least at the scale of preons. Tests for composite W's and Z's are discussed in e.g. refs.[14,15]. The properties that I will explore are based on the assumptions that 1)preons are confined by a new confining force that we call Precolor and that 2)at the confinement scale  $M (\geq \text{few TeV})$ , the symmetries of the vacuum state permit unbroken chiral symmetries that include  $SU(3) \times SU(2) \times U(1)$  with quarks and leptons appearing in the familiar representations (plus perhaps additional families as well as exotics - for tests involving exotics see ref.[8] ).

At low energies a model independent approach is the method of effective Lagrangians.

$$L_{eff} = L_{standard} + L_{non-renormalizable},$$

where the first part describes the standard model (without the Higgs, in this approximation), while the second part is suppressed at low energies by powers of  $1/M$ , for dimensional reasons. If  $M$  is sufficiently low the second part gives rise to a number of effects that represent deviations from the standard model. These include rare decay modes and mixings,

anomalous magnetic moments,  $\mu$  decay, and deviations in angular distributions in scatterings such as  $e^+e^- \rightarrow \mu^+\mu^-$ ,  $b\bar{b}$ ,  $t\bar{t}$ . I will argue that there is evidence for  $M \geq 3$  TeV, and that the SLC, LEP I, LEP II can be sensitive to scales as high as 20-25 TeV.

At energies close to or above the scale  $M$  we expect a dramatic manifestation of the new strong interaction with cross sections much above the QCD background, and with the possible appearance of a whole new set of heavy states that can cause resonances in cross sections. I will argue that if  $5 < M < 20$  TeV, the SSC is expected to easily see detailed evidence of compositeness. If  $M$  is larger, the SSC remains sensitive up to  $M \sim 100$  TeV.

In this analysis it is useful to make analogies between the new confining force and QCD. For example, confinement through precolor flux tubes would lead to a spectrum of heavy states that lie on approximately linear Regge trajectories [5], as is known to be the case experimentally in QCD. This is illustrated in Fig.1.

Fig.1 - Approximate spectrum of composites.

Note the massless composite fermions with spin-1/2 that result from unbroken chiral symmetries. We will choose  $M$  to correspond to the mass of the first heavy vector meson composed of preon-antipreon. This is the analog of the rho in QCD. Furthermore, in the energy regime  $E \sim M$  we may model our strongly interacting amplitudes by analogies to low energy strong interactions involving the concepts of resonances, Regge exchanges, Pomeron (precolor glueballs), all of which are approximately representable by a version of the dual resonance model [5]. The low energy limit of these amplitudes are arranged to reproduce the effective non-renormalizable interactions that appear in the effective lagrangian above. Thus, the low and high energy analysis of composite models are correlated. At energies  $E \sim M$ , QCD and the electroweak interactions are negligible relative to the strong precolor interaction. Therefore they can be accounted for perturbatively in the same way that the electroweak interactions are a perturbation on QCD at energies of a



few GeV. By contrast, at low energies the effects of the short range (confined) precolor interaction is negligible, and the standard model interactions dominate, as observed in our present energy regime.

In both the low energy as well as the high energy analysis the assumed (nearly) unbroken chiral symmetry plays a major role. First, since it is an (nearly) unbroken symmetry, it helps classify the massless as well as the massive states. For the massive states, this implies the existence of nearly degenerate (as compared to  $M$ ) particles with different flavor- color-family quantum numbers, since the breaking scale in these quantum numbers for the usual quarks and leptons is much smaller than  $M$ . For an SSC scale analysis this has some obvious implications. It would suggest that leptoquarks, family changing vector bosons, colored vector mesons, etc. would be at approximately similar masses, and could give rise to interesting signals [6]. Second, at both low and high energies, the unbroken chiral symmetry provides a method for classifying the interactions. For example, in the effective low energy lagrangian, the 4-fermi interactions must obey chirality and also must be invariant under the surviving non-abelian chiral transformations. The same is true at high energies. The invariant amplitudes must be classified according to chirality and the non-abelian symmetries, as in ref.5. The low energy limit of these amplitudes reproduce the 4-fermi interactions, thus insuring compatibility of the low and high energy analyses.

## 2. A MODEL FOR LEPTON-QUARK SYMMETRY

Before discussing tests it is useful to illustrate the construction of preon models by giving an example. In this section I will discuss a model that addresses the puzzle known as the "lepton- quark symmetry". I will propose a model which clarifies this "symmetry" and in particular justifies why leptons have no color while quarks have it, without apriori putting in this information "by hand". To my knowledge this particular question was not resolved and only minimally discussed in previous preon models or any other recent ideas that go beyond the standard model, and this is part of the reason why I am presenting this model in this talk. The model has other features which help in the solution of other problems connected with low scales of compositeness, as will be emphasized later in discussing tests and mass generating mechanisms, and thus help illustrate both the questions and possible solutions.

Consider an asymptotically free precolor gauge theory based on  $SU(4)$ . Take 3 bosonic preons  $\phi^a$ ,  $a=1,2,3$  together with  $N$  left-handed  $\psi_L^i$  and  $N$  right-handed  $\psi_R^j$  fermionic

preons,  $i,j=1,\dots,N$ , in the 4-dimensional fundamental representation of precolor. The kinetic terms of this theory automatically possess an anomaly free "flavor" symmetry  $G=SU(N)_L \times SU(N)_R \times U(1)_V \times SU(3) \times U(1)_\phi$ . According to  $SU(4) \times G$  we classify

$$\psi_L = (4; N, 0, 0)_0; \quad \psi_R = (4; 0, N, 0)_0; \quad \phi = (4; 0, 0, \bar{3})_{-1/6}$$

where the subscript indicates the  $U(1)_\phi$  charge, while the  $U(1)_V$  is not indicated since it is obvious. We assume that the  $G$  symmetry remains unbroken (this cannot be proven with available techniques at this stage, except for consistency conditions which are satisfied) and consider the  $G$ -classification of the following precolor singlet composites:

$$\begin{aligned} (\psi_L \bar{\phi}) &= (N, 0, 3)_{1/6}; & (\psi_L \phi \phi \phi) &= (N, 0, 0)_{-1/2} \\ (\psi_R \bar{\phi}) &= (0, N, 3)_{1/6}; & (\psi_R \phi \phi \phi) &= (0, N, 0)_{-1/2} \end{aligned}$$

The  $SU(3)$  symmetry in this classification will be interpreted as the familiar color and will be gauged. Thus the first line corresponds to  $N$  left handed quarks and leptons while the second line corresponds to  $N$  right handed ones. There is a complete quark-lepton symmetry. The leptons are not a-priori required to be color singlets "by hand", but rather it is the requirement of confinement in precolor singlets (via the  $SU(4)$  Levi-Civita symbol) and Bose statistics for the  $\phi$  preons which require that leptons *emerge* as singlets of color. This mechanism provides an *explanation* of colorless leptons, as opposed to simply introducing extra preons associated with leptons, or putting in leptons "by hand" through large symmetry groups, as in grand unified groups.

Furthermore, the existence of the leptons is *required* by anomaly matching of the "flavor" symmetries listed above. For example the  $(\psi \bar{\phi})$  composites by themselves cannot match the triangle anomalies of  $(SU(N)_L)^3$  or  $(SU(N)_R)^3$  between preons and quarks. The lepton composites are needed to just match these anomalies (i.e. there are 4 preons and also 4 composites in  $N$  of  $SU(N)_L$ , etc.) . The matching of the remaining anomalies is also non-trivial but do not require conspiracy between quarks and leptons, but rather they require conspiracy between left and right handed composites. Thus the  $SU(3), U(1)_\phi$  as well as the mixed  $(SU(N)_L)^2 \times U(1)_\phi$  etc. triangle anomalies, which are all trivially zero on preons term by term, become zero on composites only by cancellation between lefts and rights.

Another nice feature is the quantization of the  $U(1)_\phi$  quantum number on quarks and leptons in the form  $1/6; -1/2$ . We will relate this  $U(1)$  to the  $U(1)$  in  $SU(2) \times U(1)$  of the standard model, thus explaining charge quantization of quarks versus leptons naturally.

To reproduce the gauge weak interactions of the standard model, we re-group the preons as follows. Let  $N=\text{even}$  (e.g  $N=6$ ) and take the left handed  $\psi_L$  in groups of two which will be assigned to doublets of a gauged  $SU(2)_L$  embedded in  $SU(N)_L$ . Thus there will be  $N/2$  (e.g  $N/2=3$ ) such doublets of preons which will result in  $N/2$  left handed doublets of quarks and leptons. Similarly, we can identify a right-handed  $SU(2)_R$ , and we will be interested in the generator  $T_{3R}$  embedded in this group. Then the hypercharge generator  $Y$  of the standard model is identified as the linear combination of  $T_{3R}$  with the generator  $K$  of  $U(1)_\phi$ ,  $Y = T_{3R} + K$ . The  $U(1)$  generated by  $Y$  will be gauged. Thus under the gauged  $SU(3) \times SU(2)_L \times U(1)_Y$  we find that the composite quarks and leptons fall into the familiar classification, with  $N/2$  repetitive families. The number of families ( $N/2$ ) is put in by hand in this model.

The gauging of  $SU(2) \times U(1)$  breaks the  $SU(N)_L \times SU(N)_R \times U(1)_V$  symmetry to  $[SU(2)_L \times U(1)]_{\text{gauged}} \times [SU(N/2)_L \times SU(N/2)_{U_R} \times SU(N/2)_{D_R} \times U(1) \times U(1)]_{\text{global}}$ . The global part of this symmetry acts as a family group. Each of these  $SU(N/2)$ 's act simultaneously on quarks and leptons. The one labelled by  $L$  acts on doublets, the ones labelled by  $U, D$  act on the right handed counterparts of the "up" and "down" members of the doublets. This type of symmetry group is very desirable in order to implement a GIM-like mechanism after mass generation, as will be discussed further below.

If desired, we can put more structure in our model by reinterpreting some of the  $N/2$  families as technicolored composite fermions by letting them carry technicolor quantum numbers in order to assist in a dynamical mass generation mechanism as will be alluded to later. Thus, we might arrange to have 3 families and a technicolor group  $SU(t)$  which is vector-like, by taking  $N/2=3+t$ .

We will return to properties of this model below when discussing limits on the scale  $M$  and a mass generating mechanism. But first let us examine some limits on  $M$  in a model independent approach.

### 3. LIMITS AND TESTS AT LOW ENERGY

#### 3.1. 1. Rare Processes

We start with the 4-fermi interactions in the effective Lagrangian.

$$\frac{\lambda_{1234}^2}{2M^2} (\bar{\psi}_1 \Gamma \psi_2) (\bar{\psi}_3 \Gamma \psi_4)$$

which can be thought of as arising from the low energy limit of amplitudes that may be represented by preon duality diagrams. For example, for the model in the previous section we have the types of processes depicted in Fig.2 for quark (q) and lepton (l) scattering.

Fig.2 - a)  $q\bar{q} \rightarrow q\bar{q}$ ; b)  $q\bar{q} \rightarrow l\bar{l}$ ; c)  $l\bar{l} \rightarrow l\bar{l}$

In specific models, these 4-fermi interactions must be taken consistent with the unbroken preon flavor symmetries G. When these symmetries allow the 4-fermi terms listed below, then the corresponding limits on the table are obtained [4,5]. (These are the most severe restrictions, for additional processes see ref.[11].)

4-fermi term	Process	Limit $M \geq$
a) $\bar{e}d\bar{u}u^c$	proton decay	$\lambda \times 10^{13}$ TeV
b) $\bar{s}d\bar{s}d$	$K^0 - \bar{K}^0$ mixing	$\lambda \times 400$ TeV
c) $\bar{c}u\bar{c}u$	$D^0 - \bar{D}^0$ mixing	$\lambda \times 50$ TeV
d) $\bar{s}d\bar{e}\mu$	$K^+ \rightarrow \pi^+ \bar{\mu}e, K_L \rightarrow \mu e$	$\lambda \times 30$ TeV

where  $\lambda$  stands for  $\lambda_{1234}$  for the appropriate process. When the symmetries allow  $\lambda \neq 0$  the underlying strong precolor interaction suggests the magnitude  $\lambda^2/4\pi \approx 2$  in analogy to  $\rho$  exchange in QCD. It is clear that, for a model whose symmetries do not eliminate all of the processes above, M would be required to be above at least 100-150 TeV. Such a model would not be testable in the foreseeable future. Therefore it is crucial to hunt for models whose symmetries require  $\lambda = 0$  or suppressed for all the rare processes above. Although a), b), c) can be avoided by symmetries in classes of models, it is very hard to completely eliminate d), as discussed in refs.[4,5]. This problem is intimately connected to family replication. Whatever mechanism replicates the electron to the muon is likely to

replicate the down quark to the strange quark. Then family, lepton and downness quantum numbers will be separately conserved by d), and therefore this term will be present. There may be ways of avoiding the problem. Possible cures were suggested in the past either by dissociating the replication of quarks from the replication of leptons (this means usually more preons), or by appealing to lucky accidents in the mass matrix in the presence of extra families, as discussed in refs.[7,16].

However a more attractive possibility emerges in a model of the type discussed in the previous section, in which the structure of quarks and leptons are quite different: Examining the processes in Fig.2, it is evident that the amplitudes for 4-quarks is different than 2-quarks plus 2-leptons or 4-leptons. It is possible, through a Zweig-rule suppression mechanism, or lack of overlap of lepton wavefunctions with quark wavefunctions, that  $q\bar{q} \rightarrow l\bar{l}$  is suppressed relative to  $q\bar{q} \rightarrow q\bar{q}$ . If we can get a suppression factor of 10-30 in  $\lambda$  from this mechanism then the above table indicates that for such a model the processes in d) cease to put a severe restriction on the preon scale M. This probably implies also that  $l\bar{l} \rightarrow l\bar{l}$  is even smaller, so that e+e- experiments (that will be discussed below) may not put any severe constraints on M in such a model. Only the  $q\bar{q} \rightarrow q\bar{q}$  amplitude which is relevant for purely hadronic experiments (e.g. at the SSC) would be sufficiently large to yield measurable effects at the accessible energies.

In some of the models of ref.[3] there is still a different suppression mechanism at work. In this case the first two generations are composites at a much larger scale (they are practically structureless) as compared to the compositeness scale of the third or fourth generation, which is comparable to our M. However the physical states contain small admixtures of these. Therefore the 4-fermi interactions among 1st and 2nd families is suppressed by a factor  $(\sin\alpha)^4$  and those involving two fermions from 1st or 2nd and two fermions from 3rd or 4th generations are suppressed by  $(\sin\alpha)^2$ . Thus, process d) is suppressed by  $(\sin\alpha)^4$ . An estimate of the mixing angle  $\alpha$  and the mass scale M leads these authors to believe that if process d) is not seen in the next round of experiments at Brookhaven it would eliminate their model.

For the rest of this talk I shall concentrate on a model whose scale M is reasonably low so that it has measurable consequences at low energies or at least at the SSC. I will not restrict the discussion to any specific model.

### 3.2. 2. Muon Decay

If  $M$  is sufficiently low it can modify the rate for  $\mu$ -decay. The 4-fermi interaction

$$\frac{\lambda^2}{2M^2}(\bar{\mu}\gamma_\mu\nu_\mu)(\bar{\nu}_e\gamma^\mu e)$$

contributes to the decay rate. We find

$$\frac{\Delta\Gamma}{\Gamma} \approx \frac{\lambda^2}{4\pi}(1\text{TeV}^2/M^2)$$

The precision of the Berkeley-Triumph experiment puts a limit  $M > 2.9$  TeV.

### 3.3. 3. Anomalous Magnetic Moment of Muon

This has been discussed many times before [17,18]. The effective term responsible for this effect can arise only after the mass generating mechanism is turned on. Therefore, the term is proportional to the mass of the muon, and would vanish in the exact chiral symmetry limit. Dimensional considerations require the form

$$A^2 e \frac{m_\mu}{M^2} \bar{\mu} \sigma^{\mu\nu} \mu F_{\mu\nu}$$

where  $e$ , the electromagnetic charge is present since an interaction with the photon is involved, and  $A$  is a model dependent form factor. The contribution to the anomalous magnetic moment is proportional to  $(m_\mu/M)^2$ , and therefore is suppressed. The Hughes-Kinoshita analysis [10] leads to the limit  $M > A \times 0.72$  TeV. We cannot estimate  $A$  reliably, but it probably is of order 1. So this is not a very severe limit.

### 3.4. 4. Electron-Positron Scattering

The scattering cross sections for  $e^+e^- \rightarrow f\bar{f}$ , where  $f$  is any fermion, would receive corrections from 4-fermi terms of the following type

$$\begin{aligned} \frac{\lambda^2}{2M^2} [ & a_{LL}(\bar{e}_L\gamma_\mu e_L)(\bar{f}_L\gamma^\mu f_L) - c_{LR}(\bar{e}_L\gamma_\mu e_L)(\bar{f}_R\gamma^\mu f_R) \\ & + b_{LR}(\bar{e}_L\gamma_\mu f_L)(\bar{f}_R\gamma^\mu e_R) + d_{LR}(\bar{e}_L e_R)(\bar{f}_L f_R) \\ & + e_{LR}(\bar{e}_L f_R)(\bar{f}_L e_R) + (L \leftrightarrow R) ] \end{aligned}$$

where the coefficients  $a, b, c, d, e$  are generally model dependent. They are probably of order 1 if allowed by the symmetry structure of the model (note, however, the suppression

mentioned above in part 1., which can arise in certain models, such as the one presented in the previous section, or ref.3. In this section we assume no such suppression). Note that the last five terms obtained by interchanging left with right have coefficients that are generally different than the ones appearing in the first five terms. Thus, generally parity and charge conjugation invariance is violated if an underlying left-right asymmetric preon model violates these symmetries through its precolor interactions. It is very interesting to hunt for such P or C violating effects that are expected to increase with energy and eventually overcome the P and C violation effects of the weak interactions. The coefficients b,d,e tend to violate chirality, therefore they would be identically zero in many models (i.e. they are of order  $m_f/M \times m_e/M$  to some power). However there would also be many models for which chirality operations should simultaneously be applied to the electron and some other fermion (e.g muon) because they may share the same preons. For those cases, even though masses would be prevented, certain 4-fermi interactions, like the coefficients of b would be allowed. It is hard to imagine that d or e-type interactions would be allowed. Therefore, we will assume that d and e are negligible, but will include b in our analysis (keeping in mind that for certain models it will be zero). The coefficients a,c are always allowed since they cannot be prevented by any symmetry. It is possible to analyze models by drawing preon diagrams (analogous to duality diagrams) and obtain relative ratios between a/b/c that correspond to a simple counting of the number of diagrams contributing to each chirality projection above. This kind of analysis was introduced [5] at the level of the higher energy amplitudes but can equally apply at the low energy limit.

Eichten, Lane and Peskin [19] estimated the deviations in Bhabba scattering that would be caused by a model with nonzero  $a_{LL}$ . They found observable deviations at low energies (PEP, PETRA) if the scale M is low. For agreement with measurement it has been found that  $M > 2-3$  TeV. In collaboration with Gunion and Kwan [20], we extended this analysis to include effects of polarization and analyzed the more general model with all allowed coefficients. We found that if sufficiently precise measurements of angular distributions are performed the sensitivity of the SLC and LEP-I to compositeness would extend to  $M < 7$  TeV. Such measurements, if they yield any deviations from the standard model, would be capable of also disentangling partially the coefficients a,b,c and measuring the possible left-right asymmetry in these coefficients. The analysis of ref.12 was not very sensitive to the amplitude b which, as remarked above may be present in some models. Together with Eilam and Gunion [21] we suggested polarized beam processes that are sensitive to this amplitude. Since there is no standard model background for this amplitude

any effect at all would be interpreted as new physics. It appears, however, that after taking into account various restrictions from  $SU(2) \times U(1)$ , and estimating possible contributions from the amplitude  $b$  to the electron mass, it is not easy to get a measurable effect that is due solely to this amplitude, although it may be worth a try [see ref 21]. In our work in ref.[21] we also extended the analysis of refs.19,20 to the energies applicable to LEP-II. As illustrated in table 1, if  $M < 25$  TeV, the *unpolarized* cross section would show impressive deviations from the standard model at the higher center of mass energies. The quantity that is tabulated is  $\Delta$ , as defined below, which is the percentage deviation of the cross section from the standard model in the reaction  $\bar{e}e \rightarrow \bar{t}t$  (similarly for other heavy quark pairs),

$$\Delta(\cos\theta) = \frac{(d\sigma/d\Omega)}{(d\sigma/d\Omega)_{st}} - 1$$

The deviation  $\Delta$  is given at center of mass energies ranging from 100 to 200 GeV and at certain backward angles ( $\cos\theta$ ), where it is large. It is even larger at larger backward angles.

$\cos\theta$ E(GeV)	M(TeV)				
	5	10	15	20	25
-0.4 100	-0.003	-0.001	-0.001	"0"	"0"
-0.7 110	-0.017	-0.010	-0.005	-0.003	-0.002
-0.8 120	+0.077	-0.003	-0.003	-0.002	-0.002
-0.8 150	+1.35	+0.192	+0.074	+0.039	+0.024
-0.7 200	+3.55	+0.49	+0.185	+0.098	+0.061

It seen that, even for compositeness scales as high as 20 TeV, LEP-II can detect 9.8mass energies of 200 GeV and  $\cos\theta=-0.7$ , and larger deviation at larger backward angles. Therefore, *such measurements will set the mood for prospects of discovering compositeness at the SSC*. It must be understood that these remarks apply provided there is no suppression mechanism for 4-fermi interactions involving leptons, as in Fig.2. If there is such suppression then the bounds on  $M$  should be relaxed accordingly.

#### 4. A SCHEME FOR MASS GENERATION

The main theoretical emphasis in composite models has been on obtaining massless composite fermions. Assuming that such a model has been constructed, there still remains to understand the origin of mass of quarks and leptons.



It is attractive to speculate that the  $SU(2)$  breaking required to generate masses for the  $W$  and  $Z$  has its origin in a dynamical theory of technicolor, which requires technifermions. It was suggested some time ago by Bars [22,2] and Preskill [23] that the technifermions might be composites of preons and that the  $SU(2)$  breaking may be transmitted to the quarks and leptons via the effective 4-fermi interactions involving two composite technifermions and two composite quarks or leptons. It was later suggested by Bars [7] that in this scheme high color representations of ordinary  $SU(3)$ -color composite fermions (which may be born simultaneously with the quarks and leptons in the same model) may provide the same mechanism as technifermions, thus providing a more economical mechanism without introducing technicolor as an additional force.

Recent work by Chivukula and Georgi [24] has expanded on the technicolor version of this scheme (but their remarks can be extended to the high-color-representation scheme as well). They are concerned with the implementation of the GIM mechanism and suggest, at the 4-fermi level, an  $(SU(3) \times U(1))^5$  family symmetry which would guaranty that no dangerous neutral current interactions are generated. Thus, they require an  $SU(3) \times U(1)$  family symmetry separately for each of the following: left-handed quark doublets, right-handed charge  $2/3$  quarks, right-handed charge  $-1/3$  quarks, left-handed lepton doublets, and right-handed charged leptons. Then they remark that the type of 4-fermi term that would generate masses for quarks and leptons (after technifermion condensation) breaks this symmetry and is of first order in preon masses (which are assumed to arise from some unspecified symmetry breaking mechanism). Since a preon mass must appear in the numerator, for dimensional reasons an extra power of the precolor scale  $M$  must appear in the denominator. Thus, these terms are proportional to  $\lambda^3 m / (4\pi M^3)$ , where  $m$  stands for the preon mass matrix in the up, down, or charged lepton sector, as appropriate. None of the preon masses  $m$  can exceed  $M$  since otherwise there would be no reason to expect a dynamically unbroken chiral symmetry that protects the quarks and leptons from acquiring a dynamical mass of order  $M$ . This reasoning allows one to put an upper limit on  $M$  by considering the lower limit on the top quark mass  $m(\text{top}) > 23 \text{ GeV}$ . After translating the conventions of ref.[24] to my conventions, their limit implies that the precolor scale should be bounded by  $M < (7 - 10) \text{ TeV}$ .

A few remarks are in order. First, the Chivukula-Georgi symmetry is too large to achieve economically in preon models (no such economical model is known to this author). It is likely that this symmetry requires separate preons for every quark and lepton. Then there is the danger that almost none of the puzzles that preon models are hoping to

answer would be answered. Thus, I suggest that a smaller symmetry would be sufficient if dynamical (rather than symmetry) mechanisms suppress the 4-fermi interactions involving two quarks and two leptons. A model in which this may be true was presented in one of the previous sections of the present paper (see discussion about Fig.2). Then it is enough to have three SU(3) family symmetries that act on the left-handed quark doublets, the right-handed charge 2/3 quarks and the right-handed charge -1/3 quarks. These SU(3)'s may simultaneously act on the leptons as well. If they do act simultaneously on quarks and leptons they allow certain undesirable 4-fermi couplings for two quarks and two leptons. But assuming that these are sufficiently suppressed they cause no harm from the point of view of existing bounds. These SU(3)'s are sufficient to implement the GIM mechanism and they can be achieved quite economically as illustrated in the above model. Other models that included this kind of symmetry were constructed before [2,7], and the role of the symmetry for the GIM mechanism was commented on in refs.[7,20].

A second remark concerns the ratio of 4-fermi couplings involving two technifermions and two quarks versus two technifermions and two leptons. These could be very different from each other. In a model of the type presented above the coupling involving leptons is likely to be much smaller. This is good because it has the potential for explaining the smallness of lepton masses versus quark masses.

A third point is that certain 4-fermi interactions involving two ordinary quarks and two ordinary leptons must also be taken into account in the analysis of the mass matrix. When we close the quark legs with a massive propagator for the quarks this generates a mass for the leptons, and similarly when we close the lepton legs it generates a mass for the quarks. The momenta involved in such loops should be cutoff at the technicolor scale rather than the precolor scale, since the massive propagator is sensitive to technicolor. The type of 4-fermi interaction that may do this preserves the total chirality of quarks plus leptons but not of each separately. This type of 4-fermi term was discussed in ref.21; an example which preserves SU(2)xU(1) is  $\bar{Q}_L b_R \bar{e}_R l_L$ , where  $Q_L$  is the top-bottom quark doublet and  $l_L$  is the neutrino- electron doublet. If the bottom loop is closed with a massive b, and a cutoff used, this generates a small mass for the electron, of the right order of magnitude.

Thus, we see that a variety of 4-fermi terms may participate in the mass matrix and could give interesting mass patterns. Further research using this approach is warranted. For this mechanism to be useful, the precolor scale must be reasonably low. This is encouraging from the point of view of being able to test the model experimentally. Note however that if leptonic 4-fermi couplings are suppressed as suggested by models of the type of Fig.2,

signals in electron-positron annihilation experiments will also be suppressed even though the precolor scale is low. Then it is the hadronic machines that would have a better chance of testing such a theory, as discussed below.

## 5. TESTS AT THE SSC

Next, I would like to report on phenomenological studies that relate to the SSC by concentrating on the reactions  $pp$  or  $p\bar{p} \rightarrow$  jets or lepton pairs. In ref.[25] EHLQ did the analysis under the assumption that compositeness interactions are represented by 4-fermi interactions. This is true if the SSC (parton+parton) energies would be far below the compositeness scale. Provided we assume this, their work produced plots of cross sections that decrease with energy, and in which the compositeness correction remains above the standard model background and detectable up to a scale of  $M \sim 20$  TeV.

However, if  $M$  is as low as 20 TeV the 4-fermi description of precolor interactions is no longer correct, and a model of energy and angle dependent amplitudes is necessary. For this purpose a model for the *scattering amplitudes* of the elementary processes among the partons (quarks, gluons  $\rightarrow$  quark pairs, gluon pairs, lepton pairs) as composed from preons was introduced [5]. The assumption was that at the SSC there would not be sufficient energies to get to the asymptotically free region of precolor interactions, so that precolor interactions should behave like the familiar strong interactions at low energies. So, we would expect resonances, regge behaviour (including a Pomeron= precolor glue balls), duality (reflecting string-like precolor confinement) and finally a low energy behaviour equivalent to the 4-fermi interaction. Furthermore the amplitudes must be consistent with the surviving chiral symmetries.

These properties are accomodated by building [5] the following chirality projected amplitudes to represent the reaction  $f_1\bar{f}_2 \rightarrow f_3\bar{f}_4$ , where the  $f$ 's are any set of fermions

$$\begin{aligned} & [A_{LL}(\bar{u}_{3L}\gamma_\mu u_{1L})(\bar{v}_{2L}\gamma^\mu v_{4L}) + B_{LR}(\bar{u}_{3L}\gamma_\mu u_{1L})(\bar{v}_{2R}\gamma^\mu v_{4R}) \\ & - C_{LR}(\bar{u}_{3L}\gamma_\mu v_{4L})(\bar{v}_{2R}\gamma^\mu u_{1R}) D_{LR}(\bar{u}_{3L}u_{1R})(\bar{v}_{2L}v_{4R}) \\ & + E_{LR}(\bar{u}_{3L}v_{4R})(\bar{v}_{2L}u_{1R}) + (L \leftrightarrow R)] \end{aligned}$$

Any 4-fermi amplitude can be put into this form after Fierz transformations. On the basis of chiral symmetry the D and E amplitudes were taken equal to zero, while the A, B, C amplitudes were taken to represent the sum of (chirality projected) preon-duality diagrams that contribute to the elementary parton process. A table of the relevant diagrams and

their contributions is found in ref[5]. The amplitudes for fermion + fermion  $\rightarrow$  fermion + fermion is obtained from the above expression by crossing symmetry, and similarly the gluonic parton amplitudes can be built [6]. Each individual preon duality diagram was represented by Veneziano model type beta function amplitude. Similar diagrams (except for their quantum numbers) were represented by the same function. There were only a few independent such functions, but as a further first approximation all of them were taken to be identical, and equal to a beta function. For the channels allowing the vacuum quantum numbers a "Pomeron" contribution was added in such a way as to insure crossing symmetry (see ref.26 for a correction). With this construction the amplitude was guaranteed to satisfy all the desired properties of resonances, Regge behaviour, duality, crossing symmetry and the correct normalization that reduces to the 4-fermi interaction at low energies.

The elementary partonic cross sections built from these amplitudes were folded with the parton distributions of EHLQ of ref.[25]. This was done numerically in collaboration with Hinchliffe [26] in the case of jet final states, and in collaboration with Gunion and Kwan [16] in the case of leptonic final states. The result is a series of plots of cross sections that show a rich structure of bumps and shoulders and, most notably, *very large cross sections, far above the QCD background*. An example of jet final states plotted versus the jet invariant mass for various values of  $M=3,6,10,20,30,\infty$  TeV is shown in the figure, taken from ref.[15]. The limit of  $M=\infty$  is equal to the pure QCD cross section.

This figure is produced under the assumption that the width of the jet-jet resonance is about 1/5 its mass, similar to the rho-meson in QCD.

The width is model dependent and also depends on the quantum numbers of the resonance. Estimates for the widths in various models appear in ref.[27]. Resonances whose widths

are larger than  $1/2$  its mass flatten out to a degree that they no longer show as a noticeable bump. If the width is smaller than  $1/5$  its mass, then higher regge recurrences also begin to show, as can be noticed slightly in the figure. Ref.[26] found out that gluonic partons were negligible, mainly because a gluon's interaction introduces powers of the QCD coupling constant, which is small compared to the strong precolor interaction experienced by quark partons. Even though the gluonic partons are much more abundant at the SSC energies, the strength of the new strong interaction completely overwhelms this factor.

Similar features apply also to lepton final states, as discussed in ref.[27].

From these results it is seen that if  $M$  is not too much larger than 20-25 TeV, then the cross section will be so large that compositeness will be easy to see at the SSC, and its features will be completely distinguishable from other "new physics" signatures at a comparable scale. In refs.[26,27] the larger values of  $M$  are also discussed. According to reasonable criteria for observing "new physics" at the SSC, it was concluded that the SSC would remain sensitive to compositeness up to scales of the order 100 to 300 TeV, and at the larger scales the lepton pairs would be a more sensitive probe.

A question which occurs is whether to expect multilepton or multijet final states to suddenly swamp the cross section if the compositeness threshold is crossed. We have argued that this could not be expected at the SSC, on the basis of confinement through precolor flux tubes [27]. The point is that there would not be enough energy available to the preons to be able to break the confining string more than one time. Furthermore, phase space provides a big suppression factor for multibody final states even if the final particles are (almost) massless. Therefore we expect that 2-body final states will dominate the total cross sections although, of course, there would be a small fraction of multibody final states whose compositeness cross section will be significantly above the QCD background for the ranges of  $M$  under discussion. Further discussion on multibody final states can be found in refs.[6,9].

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